Traceability, food safety and industry reputation*

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Abstract

Sometimes authorities are unable to identify the origin of a tainted food product. In such cases, food recalls or warnings are often applied to all suppliers which means that the recall applies to suppliers of products that do not contribute to the contamination. One benefit of traceability is to enable more targeted recalls, identifying more specifically the product's origin. In this article, we show how increased traceability contributes to protect the reputation of industries by potentially limiting the size of product recalls. Furthermore, we show the relationships between the optimal degree of traceability and the level of food safety for identical farms in a competitive industry and for an industry using collective action to set rules and standards.

Key words: Food safety, recall, reputation, traceability

JEL classification: D21, M31, Q10, Q18

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Traceability, food safety and industry reputation

Recent well-publicized food safety incidents, including those associated with fresh produce, peanuts, pistachios and imported food products, have raised interest in the traceability for food in North America. Many countries have implemented traceability systems for cattle (Souza-Monteiro and Caswell 2004). In Europe, *Regulation 178/2002* requires the traceability of all food in the European Union (European Union 2002). The pet food contaminated by melamine-tainted ingredients imported from China and the 2007 cases of melamine-tainted dairy products have raised interest in the traceability of imported food products and ingredients (Roth et al. 2008). Recently, the President's Food Safety Working Group has recommended a new national traceback and response system to deliver food safety alerts to consumers (President's Food Safety Working Group 2009).

One collective, industry-wide motivation for improved traceability is the protection of the general reputation of an industry from negative demand shocks caused by food safety incidents. The finding of *E. coli* tainted spinach in September 2006 illustrates the potential role for traceability to protect the reputation of an industry. Soon after spinach was identified as the vector of *E. coli*, the contaminated spinach was traced to Natural Selection Foods as the packer. However, because the Food and Drug Administration (FDA) was unable to rapidly identify the farm source of the outbreak and to isolate the contaminated spinach, it advised consumers on September 14 not to eat bagged spinach. Stores did not limit their response to the bagged product and pulled all fresh spinach from the shelves (CDC 2006). The farm of origin was only identified with further extensive investigation. However, the precise means by which spinach was contaminated could not be identified. The delivery of tainted spinach by one grower caused the largest recall ever for leafy-green products (USDA Agricultural Marketing Service 2007). Six months after the outbreak, the retail sales of bagged spinach were still below the previous year level while the consumption of bunched spinach had rebounded (Calvin 2007).

The recent *Salmonella* Saintpaul outbreak in tomatoes or jalapeno peppers is another example of how a single food safety event can affect an entire industry. After some consumers reported illness associated with food consumption, the FDA first warned consumers not to eat certain types of tomatoes on June 3, 2008. Consumers responded by cutting consumption and tomato prices dropped. On June 27, the FDA admitted that tomatoes may not have been responsible for the outbreak. In fact, the FDA could not find samples of contaminated tomatoes. The investigation was then broadened to products often consumed with tomatoes such as cilantro and jalapeno peppers. The warning on certain types of tomatoes was lifted on July 17, a month and half after the first warnings were given. The FDA announced on July 21 that it had found a sample of jalapeno peppers contaminated with the *Salmonella* Saintpaul. A recall was immediately initiated. Flanders (2008) finds that the demand for tomatoes was significantly affected by the *Salmonella* outbreak.

On March 25, 2009 the FDA recommended that consumers not consume pistachios or pistachio-containing products. This announcement was made following the discovery by a Kraft supplier, Georgia Nut Company, that a sample of pistachios delivered by Setton Pistachios had tested positive for four strains of *Salmonella*. The FDA recommended that consumers avoid eating pistachios and pistachio-containing products from all origins. No case of foodborne illnesses related to *Salmonella* contaminated pistachios has been reported and only a single sample of pistachios has tested positive for *Salmonella*. The strong reaction of the FDA came at a high price for the pistachio industry and the economic consequences are not yet known.[1]

These examples of food safety incidents show how a single source food contamination can affect an entire industry because of a lack of traceability. For instance, if the origin of the contaminated spinach had been identified quickly, a much smaller quantity

[1] At the time of the discovery of *Salmonella* in pistachios, the FDA was facing harsh criticism after the case of *Salmonella* in peanut butter.

of spinach could have been removed from the market, a smaller share of the industry could have been affected, and consumers could have been provided with information much sooner. Delays in traceability can have important consequences for an industry.

This article examines analytically how traceability systems that protect the general reputation of an industry affect food safety and profits. In the model developed in this article, the safety reputation of a food industry, defined simply as a group of firms (farms) producing a homogenous food product, is challenged by randomly occurring food safety incidents. Unlike Pouliot and Sumner (2008), we do not deal with the traceability of food through a supply chain. Also, unlike Resende-Filho and Buhr (2008) we do not deal with contractual arrangements and the potential for traceability to reduce information asymmetry. Rather, we focus on how food safety incidents affect demand and how the potential rapid traceback of food affects food safety and profits under alternative demand specifications.

The reputation models of Winfree and McCluskey (2005) and Carriquiry and Babcock (2007) are applied to the choice of food quality. In the differential game model of Winfree and McCluskey (2005), collective reputation depends on the average quality of food delivered by a group of firms in past periods. There is no traceability to the firm of origin such that firms cannot differentiate their product by quality. A firm's investment in quality is diluted among all firms in the industry. The model of Carriquiry and Babcock (2007) considers that firms can implement Quality Assurance Programs of varying stringency. In their duopoly scenario, Carriquiry and Babcock (2007) find that firms invest less in Quality Assurance Program when reputation is public, i.e. there is no traceability to the firm of origin, than when reputation is private, i.e. perfect traceability to the firm of origin.[2]

[2] Our model and the models of Winfree and McCluskey (2005) and Carriquiry and Babcock (2007) differ from much of the reputation literature where the focus is on how a reputation is established and how reputation can be used strategically. For instance, in Klein and Leffler (1981), reputation may serve to enforce contracts without a third party enforcer. Kreps and Wilson (1982) and Milgrom and Roberts (1982) show that reputation effects can be obtained in their finite horizon models of entry deterrence if

In our model, output is sold in two marketing periods and each farm plans to deliver food in each period. Before delivery in the second marketing period however, each unit of food delivered in the first period is found to be safe or unsafe. When traceability is successful, only farms that delivered safe food in the first marketing period can sell their product in the second marketing period. If the traceability of unsafe food to the farms of origin is not successful, all farms are deemed *potential* sources of unsafe food and food supplied by every farm is withdrawn under an industry-wide recall or recommendation by health authorities to avoid consumption of the food product.

For simplicity, we consider that unsafe food is always detected but traceability may fail to identify the origin of contaminated food.[3] The model in this article builds on the absolute response of food safety authorities when there is doubt about the safety of food. The model assumes that rather than leaving any potentially contaminated food in the market, authorities recommend the removal of all suspect food or recommend that consumers stop consuming the food product. The recent cases of *E. coli* in spinach, *Salmonella* in jalapeno peppers, and *Salmonella* in pistachios are examples of the strong reaction of food safety authorities.

We compare the profit maximizing level of food safety for identical farms in a competitive industry and for a collective industry-wide organization that maximizes the profit of its members. We investigate how the incentives for farms to deliver safe food change when food traceability is augmented. We show that under some demand specifications, farms' expected revenue may increase when food is less safe and therefore more product is withdrawn from the market. We demonstrate that, in some cases, farms acting collectively have a reduced incentive to supply safe food compared to farms acting individually when traceability is increased. We find that an industry organization does

information is imperfect. In Tirole (1996), the reputation of a group is determined by the action of its members.

[3] The models of Starbird (2005) and Starbird and Amanor-Boadu (2006) allow for errors in the detection of contaminated food. The authors also allow for false positive such that safe food can be found to be contaminated.

not increase profits by using traceability strategically to induce farms to reduce food safety. Furthermore, we show that an industry organization increases traceability by more when individual farms under-supply food safety.

Definition and setup of the model

We consider farms that deliver food over two marketing periods which we refer to as marketing period 1 and marketing period 2.[4] Figure 1 shows the sequence of events in the model. We explain details of the sequence of events and other model specifications in this section.

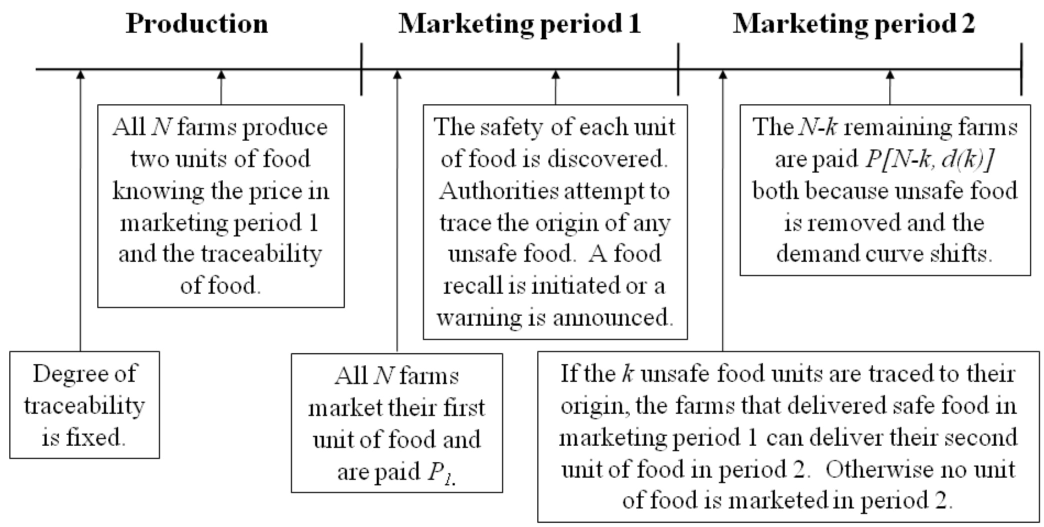

Figure 1. Sequence of events in the model

Each of the N identical risk-neutral farms produces two units of food, delivers one unit of food in marketing period 1 and is prepared to deliver one unit of food in marketing period 2.[5] Safety is measured by the probability that food is safe. Being identical, every firm has the same chance of producing unsafe food. The safety of the

[4] We apply the model to a group of identical farms but the model can also apply to any firms that deliver a homogenous product.

[5] It is a common assumption in the literature on product quality to normalize the production to one unit (for example Pouliot and Sumner 2008). Antle (2001) briefly discusses the choice of food safety and output by competing firms in the short- and long-run and shows that the relationship between output and food safety may either be positive or negative.

food delivered by a farm in marketing period 1 is the same as the safety of the food delivered in marketing period 2. Thus, if food delivered by a farm in marketing period 1 is unsafe, the food would have been delivered by that farm in marketing period 2 is also unsafe.[6]

At delivery, a farm does not know whether its output is tainted or not.[7] Before the beginning of the second period, the safety of food delivered in the first period is discovered and a governmental agency attempts to trace the contaminated food to its origin.

Traceability refers to the ability to trace the origin of a food product. Traceability is accurate in the sense that an innocent farm is never accused and a guilty farm is never exonerated.[8] The *degree of traceability* is simply the probability of identifying the farm of origin.[9] Let $T \in [T_{\min}, 1)$ be the probability that the product of a farm can be traced to its origin. Background traceability, $T_{\min} \geq 0$, is the degree of traceability when no food traceability system is implemented and farms spend no resources on traceability.

When delivering its unit of output in period 1, a farm knows that if its product is unsafe, it will be accurately traced back with probability T. The same degree of traceability applies to all farms.[10] Note that the traceability system fails to identify the origin of a tainted unit of food with probability $1-T$. Therefore, farms know that even if their own food turns out to be safe, the lower the degree of traceability, the more likely it is that a food safety incident originating from a single farm blocks sales in marketing period 2 for every farm in the industry.

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[6] Alternatively, we could assume that the safety of food in marketing period 1 is not perfectly correlated with the safety of food in marketing period 2. This would imply that some unsafe food is marketed in period 2. This alternative assumption does not affect our results.
[7] We also use words "tainted" and "contaminated" to describe unsafe food.
[8] We relax the assumption of accurate traceability in appendix B and show that errors in traceability do not affect our results.
[9] We consider here that traceability is either successful or not. In some situations, traceability success increases when investigators can use time-intensive technologies. However, the current model does not deal with the dynamics of traceability.
[10] The use of traceability and food safety as a means of differentiation is the subject of further research.

The market price

The equilibrium prices of food in marketing periods 1 and 2 are determined by the intersection of demand and supply. For simplicity, in the first marketing period, all food is considered safe by buyers and every farm is paid a price P_1.[11] Each of the N farms sells one unit of food in marketing period 1. Thus N is also the total quantity of food in the first marketing period.

The safety of food bought in marketing period 1 is discovered by buyers and the recall agency before the beginning of marketing period 2 (see figure 1 for the sequence of events). In the second marketing period, the price paid to a farm for delivering food depends on the occurrence and on the size of a food safety incident in the first marketing period. When k farms other than farm i deliver unsafe food in marketing period 1, the price received by farm i in marketing period 2 depends on whether the defective products can be traced to their origin. Only the farms that delivered safe food in marketing period 1 are allowed to deliver one unit of food in marketing period 2. In the case where all the unsafe food is traced, the equilibrium price of food in the second marketing period is $P[(N-k), d(k)]$, where $(N-k)$ is the quantity of safe food when k farms deliver unsafe food and $d(k)$ is a demand shifter that reflects the perceived reliability of the industry by buyers when traceability works. If no unsafe food is detected in marketing period 1, the price of food in marketing period 2 is $P[N, d(0)] = P_1$. For simplicity, when unsafe food cannot be traced to its origin, all farms are considered as the potential supplier of unsafe food and no farm can sell food in the second marketing period.[12]

The model focuses on the choice of food safety by farms rather than on the socially optimal level of food safety. Thus, this model does not deal with the health consequences

[11] Assuming that all food is considered safe by buyers serves as a baseline and does not affect our results. We could alternatively consider that some share of farms is expected to deliver unsafe food in marketing period 1. This would simply involve a different scaling of the price in marketing period 2 and not affect any results of the model.

[12] The seemingly extreme assumption that a lack of traceability precludes any marketing was approximately satisfied in the 2006 spinach case. Moreover, the results of our analysis change only slightly if some products are sold in marketing period 2 even if complete traceability was not successful.

of unsafe food but recognizes that the detection of unsafe food in marketing period 1 affects the demand in marketing period 2.[13]

The price in marketing period 2 is a decreasing function of the quantity of safe food marketed, $\partial P[(N-k),d(k)]/\partial(N-k) < 0$. The price is an increasing function of the magnitude of the demand shift caused by the delivery of unsafe food, $\partial P[(N-k),d(k)]/\partial d(k) > 0$, where $d(k)$ is a decreasing function of the number of farms that delivered unsafe food in marketing period 1 such that $\partial d(k)/\partial k \leq 0$. Buyers revise their beliefs on the safety of food delivered by the industry in response to the number of farms that have delivered unsafe food in the first marketing period.[14]

In this model, the confidence of buyers in marketing period 2 depends only on the share of food that is found unsafe in marketing period 1, which is conveniently represented by the number of farms failing to supply safe food, k. That is, if the problem is thought to be widespread, the demand curve shifts down by more. Of course, the confidence of buyers could be influenced by other factors but we abstract from other demand shifters.

The model recognizes that k farms failing to supply safe food in marketing period 1 has an ambiguous effect on the equilibrium price in marketing period 2 when food is

[13] In our model, food is actually safe in marketing period 2. The model considers that buyers react to the announcement that unsafe food was detected. This assumption captures the fact that buyers are often not fully informed and data show that they over-react to the announcement of food safety events. Empirical evidence suggests that consumers do not react positively to the discovery of unsafe food. Examples include the long lasting effect on the demand for spinach following the September 2006 *E. coli* outbreak (Calvin 2007) and the case of pesticide contaminated milk in Hawaii in 1982 (Liu, Huang, and Brown 1998). One interpretation of the shift in demand is that consumers make Bayesian inferences on the reliability of food providers. For instance, in Böcker and Hanf (2000) consumers revise their beliefs about the reliability of suppliers at each period depending on the safety of the products those suppliers delivered in the previous period.

[14] Recall that the price in the first marketing period is set considering that all food is safe. If instead we consider that the price in the first marketing period is set considering that a number $K_1 > 0$ farms are expected to deliver unsafe food in the first marketing period, the shift in the demand can be positive if $K_1 > k$.

traced to its origin. The effect of k on the price in the second marketing period is

$$(1) \quad \frac{\partial P[(N-k),d(k)]}{\partial k} = -\frac{\partial P[(N-k),d(k)]}{\partial (N-k)}\frac{\partial (N-k)}{\partial k} + \frac{\partial P[(N-k),d(k)]}{\partial d(k)}\frac{\partial d(k)}{\partial k}.$$

We refer to the first term on the right-hand-side of (1),

$$-\frac{\partial P[(N-k),d(k)]}{\partial (N-k)}\frac{\partial (N-k)}{\partial k} > 0,$$

as the *quantity effect*. It says that the price increases when a smaller quantity of food is made available to buyers (the demand curve slopes down). This effect recognizes that farms whose products are not recalled or otherwise remain on the market benefit when competitors' products are removed. We label the second term on the right-hand-side of (1),

$$\frac{\partial P[(N-k),d(k)]}{\partial d(k)}\frac{\partial d(k)}{\partial k} < 0,$$

as the *confidence effect*. This effect recognizes that the shift in demand affects negatively even those suppliers that are not responsible for a food safety problem. If the quantity effect is larger than the effect of the loss in confidence, then an increase in the number of farms delivering unsafe food increases the price. The price falls when the confidence effect dominates the quantity effect.

Figure 2 illustrates how the price in the second marketing period is determined. In both panels, k farms delivered unsafe food in marketing period 1 such that the supply shifts from N to $(N-k)$. The supply is perfectly inelastic because each farm has one unit of output and we do not consider the entry or the exit of farms. In panel a), the demand shifts from $D(0)$ to $D_a(k)$ but the equilibrium price is larger when k farms deliver unsafe food than when all food is safe because the quantity effect is larger than the confidence effect. In panel b), the demand shifts from $D(0)$ to $D_b(k)$ so that the loss in confidence is larger than the quantity effect which implies that the equilibrium price is lower when k farms deliver unsafe food compared to when all food is safe.

In the 2006 *E. coli* outbreak in spinach, the confidence effect clearly dominated the quantity effect. It appears that some consumers still did not trust the safety of spinach six months after the incident because sales of spinach were significantly below their previous-year level (Calvin 2007). The case of the discovery of Bovine Spongiform Encephalopathy (BSE or mad cow disease) in Canada in May 2003 is not a direct application of the model in this article but illustrates a case where consumers did not seem to have reacted negatively to the discovery of unsafe beef. Cattle and beef markets in the United States and Canada were highly integrated.[15] After the discovery of BSE in Canada, imports of cattle and beef from Canada were banned in the United States, reducing the supply of beef in the United States by almost 4%. However, the discovery of BSE in Canada did not trigger a strong negative reaction for beef as a whole from American consumers and the quantity effect dominated the confidence effect, driving the price of beef up (Mathews, Vandeveer, and Gustafson 2006).

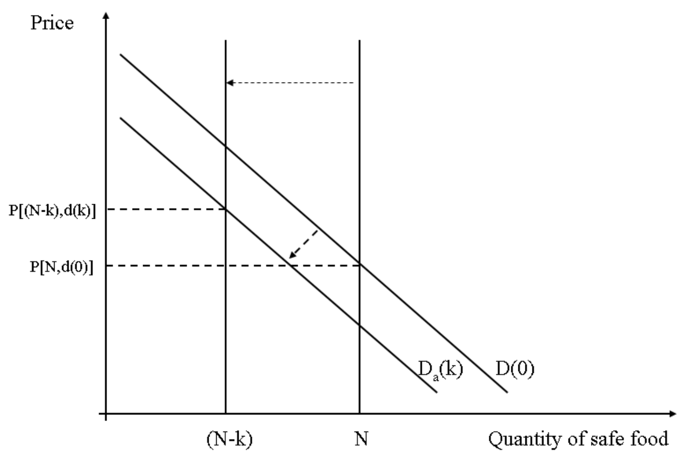
The expected revenue of farms

The production of unsafe food is accidental but farms can devote resources to food safety and reduce the probability of unsafe food. The food supplied by a farm i in both marketing periods is safe with probability ρ_i and tainted with probability $(1-\rho_i)$. The probability that a farm i delivers safe food is independent of the probability that farm j delivers safe food. Since an unsafe food item occurs randomly and all farms are identical, ρ_i is the *ex ante* probability of safety and $\rho_i = \rho_j \forall i, j$.

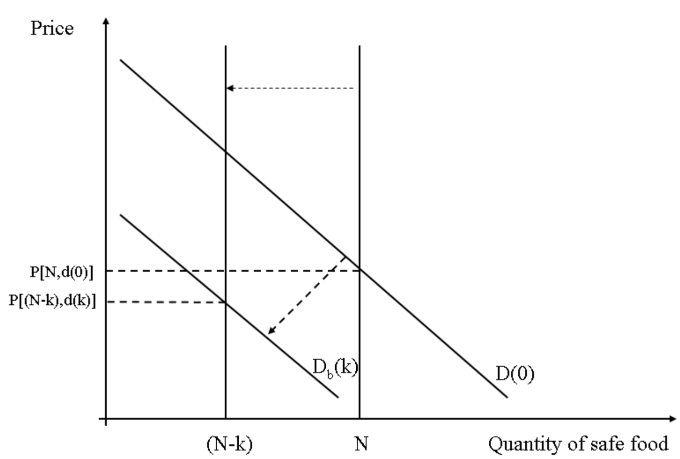
The expected revenue for a farm i in the second marketing period is

$$(2) \quad E[R_i|S_i] = \rho_i E[R_i|S_i = 1] + (1-\rho_i)E[R_i|S_i = 0] = \rho_i E[R_i|S_i = 1],$$

[15] Before the adoption of country of origin labeling requirements by the United States, Canadian beef and American beef were not differentiated.



(a) The output effect dominates the confidence effect



(b) The confidence effect dominates the output effect

Note: $P[.]$ is the price, N is the number of farms, $d(k)$ is the confidence of consumers when k farms deliver unsafe food, and $D()$ is the demand curve.

Figure 2. Equilibrium price for food in marketing period 2

where $S_i = 1$ means that the food from farm i is safe and $S_i = 0$ means that the food from farm i is unsafe. The payoff to farms that delivered unsafe food in marketing period 1 is always zero in marketing period 2 because these farms are not allowed to sell such that $E[R|S_i = 0] = 0$.[16] Therefore, the expected revenue of a farm i in marketing period 2 depends on the probability that its food is safe in marketing period 1, ρ_i, and the expected revenue given that it has delivered safe food in marketing period 1, $E[R_i|S_i = 1]$. To avoid notation clutter, we write that $E[R_i|S_i = 1] = E[R]$ such that we can write that the expected revenue for the second marketing period is

$$E[R_i|S_i] = E[R].$$

The expression for $E[R]$, accounts for the number of farms delivering unsafe food in marketing period 1 and whether traceability to the origin of the food safety problem succeeds. The probability that k farms other than farm i deliver unsafe food in period 1 is given by a binomial distribution function:

$$(3) \quad Prob(k) = \binom{N-1}{k} \rho^{N-1-k}(1-\rho)^k,$$

where $\binom{N-1}{k} = \frac{(N-1)!}{k!(N-1-k)!}$ is the binomial coefficient.[17]

Because the occurrence of unsafe food and successful tracing are independent events, the probability that each unsafe food unit from k farms is traced successfully is given by T^k. The joint probability that k farms supply unsafe food and that all the

[16] Similarly, Carriquiry and Babcock (2007) normalize the demand to zero when a farm has a reputation for delivering an unsafe food product. Such a normalization is roughly consistent with a sharp decline in the aggregate demand when consumers react to a food safety event.

[17] One alternative to the binomial distribution function is the poison distribution function: $Prob(k) = \frac{\exp^{-\lambda}\lambda^k}{k!}$, where $\lambda = N(1-\rho)$. The results are not affected by the choice of the distribution function.

contaminated food is traceable to the k farms is given by

$$(4) \quad Prob(k, \textit{Traceability succeeds}) = \binom{N-1}{k} \rho^{N-1-k}(1-\rho)^k T^k.$$

Analogously, the probability that k farms other than farm i deliver unsafe food, but that traceability to the k farms fails is

$$(5) \quad Prob(k, \textit{Traceability fails}) = \binom{N-1}{k} \rho^{N-1-k}(1-\rho)^k (1-T^k).$$

In this model, the probability of tracing a food product to farm i is independent of the probability of tracing a food product to farm j and therefore the probability of tracing a food product to its origin does not depend on the number of farms N. Moreover, traceability is used only to identify the origin of unsafe food and is not used to show that a farm is not involved in a food safety incident.

Farms delivering safe food in marketing period 1 are paid $P[(N-k), d(k)]$ in marketing period 2 when k farms deliver unsafe food and all unsafe food is traceable. Multiplying the price in period 2 with the probability expressions (4) and (5) and summing over all possible outcomes allows us to write the expected revenue of farm i in marketing period 2 for its unit of safe food as

$$\begin{aligned}(6) \quad E[R] &= \sum_{k=0}^{N-1} Prob(k, \textit{Traceability succeeds}) \times P[(N-k), d(k)] \\ &+ \sum_{k=0}^{N-1} Prob(k, \textit{Traceability fails}) \times (0) \\ &= \sum_{k=0}^{N-1} \binom{N-1}{k} \rho^{N-1-k}(1-\rho)^k T^k P[(N-k), d(k)].\end{aligned}$$

Hence, the expected revenue for one unit of food delivered by farm i in marketing period 2, given that farm i has delivered safe food in marketing period 1, depends on the quantity of safe food delivered in marketing period 1, $(N-k)$, the *ex ante* probability that food is safe, ρ, the degree of traceability, T, and the reaction of buyers in period 2 to the delivery of unsafe food by k farms in marketing period 1, $d(k)$.

The profit maximizing level of food safety for individual farms

The expected profit of a farm i is given by

$$(7) \quad E[\Pi_i] = P_1 - 2C(\rho_i, T) + \rho_i E[R],$$

where $C(\rho_i, T)$ is the cost of supplying one unit of food that is safe with probability ρ_i and traceable with probability T.[18] Farms produce one unit for each of the two marketing periods. The gains from increased traceability, through an increase in $E[R]$, occur only in the second marketing period and depend on the probabilistic occurrence of lapses in the safety of food.

Implementing a food traceability system is costly. Meeting the traceability standard set by an industry organization or by government regulation affects the cost of production per unit of food. We consider that the cost of production per unit of food depends on the safety of food and on the degree of traceability. This is denoted by $C(\rho_i, T)$. The cost of maintaining traceability per unit of food may include the cost of labeling, the cost of segregating product from different origins, and the cost of certification.[19]

[18] We do not include a discount and storage factor to the revenue in the second marketing period because its value is not of interest in the model or results.

[19] Note that there is no cost associated with liability for unsafe food in (7). Liability could easily be added to the model. However, the incentives for farms to supply safer food from expected liability would be the same as in Pouliot and Sumner (2008) and adding liability to the model would not affect qualitatively the results. Thus, for ease of presentation and to focus on the reputation effects, we ignore liability in the rest of this article. Furthermore, traceability for the allocation of liability is different than traceability to protect the reputation of an industry. It likely requires a higher degree of specificity (or precision) to assign legal liability for a food safety problem to individual farms than the specificity needed to protect the general reputation of an industry. However, the tracing process can take many months and still be the basis for establishing legal liability and imposing costs on farms. If the time required to trace is long, the damage to the reputation of an industry can be severe.

Each of the N farms maximizes its profit by choosing an optimal level of food safety before marketing its production (and since farms are identical, they choose the same ρ_i). Assuming that the safety of food is not regulated or regulation is not binding, the interior solution for the maximization of (7) by identical farms with respect to the safety of food, ρ_i, is implicitly given by

$$(8) \quad E[R] - 2C_\rho = 0,$$

where $C_\rho \equiv \partial C(\rho_i, T)/\partial \rho > 0$.[20] We assume that the marginal cost of safety increases at an increasing rate, that is $C_{\rho,\rho} \equiv \partial^2 C(\rho_i, T)/\partial \rho_i^2 > 0$, so that the second order condition for profit maximization is satisfied. We denote the equilibrium level of food safety from solving (8) as ρ^F.

The profit maximizing level of food safety for the industry collective

Industry organizations sometimes regulate the safety of food. For instance, following the 2006 *E. coli* outbreak in spinach, the leafy-green industry in California adopted a federal marketing order that mandates certain agricultural practices. Almost all the leafy-green handlers participate in the agreement (California Leafy Green Products Handler Marketing Agreement 2007). Similarly, in the late 1990s, the California pistachios industry was concerned about aflatoxin. The industry initiated a federal marketing order for California pistachios that sets mandatory testings and inspections to lower the risk of food safety incidents (Gray et al. 2005).

Consider an industry organization with the objective of maximizing the sum of farms' expected profits by choosing a uniform ρ for all farms. The profit maximizing level of food safety for the industry is implicitly given by the first order condition for

[20] Recall that $E[R]$ is not a function of ρ_i but a function of ρ_j where j is different than i. Therefore, we find that $E[R]_{\rho_i} = 0$.

the maximization of (7), replacing ρ_i with ρ because farms are identical

$$(9) \quad E[R] + \rho E[R]_{\rho} - 2C_{\rho} = 0,$$

where

$$(10) \quad E[R]_{\rho} = \sum_{k=0}^{N-1} \binom{N-1}{k} \rho^{N-1-k} (1-\rho)^k T^k P[(N-k), d(k)] \frac{(N-1)(1-\rho)-k}{\rho(1-\rho)}.$$

The difference between (8) and (9) is that the term $\rho E[R]_{\rho}$ does not appear in (8). The industry organization internalizes the effect of a change in the safety of food in marketing period 1 on the expected revenue in marketing period 2 while individual farms do not.[21]

We assume that the second order condition is satisfied such that

$$(11) \quad 2E[R]_{\rho} + \rho E[R]_{\rho,\rho} - 2C_{\rho,\rho} < 0.$$

Maximizing the profit of the industry collective by solving (9) yields ρ^I, the profit maximizing level of food safety for the industry collective.

Consider as an alternative to food safety chosen by farms a minimum food safety imposed by government regulation. Let ρ^R denote the probability that food is safe under government-imposed regulation. Here, ρ^R is exogenously determined because the government considers issues that are outside the scope of this model such as the societal cost of foodborne illnesses. We will bypass the regulatory details and simply call ρ^R the mandated level of food safety resulting from governmental regulation. If the government mandates a level of food safety that is higher than the profit maximizing level of food safety for the farms or by the industry organization, regulation is binding and $\rho = \rho^R$.

[21] The comparison of (8) and (9) is analogous to the comparison of the first order condition of competitive farms maximizing profits with respect to output to the first order condition of a monopoly maximizing profit with respect to output. That is, for competitive farms, the price is exogenous while a monopoly internalizes the effect of a change in the output on the price.

However, if the mandated level of food safety is lower than the profit maximizing level of food safety for the farms, regulation is not binding and $\rho = \rho^F$ or $\rho = \rho^I$. The comparison of ρ^F and ρ^I is the subject of the next section.

Comparison of the profit maximizing levels of food safety

Comparing equation (8) and equation (9), we observe that the ρ^F may be larger or smaller than ρ^I depending on the sign of the derivative of the expected revenue when food is safe, $E[R]_\rho$. The following proposition provides conditions for the sign of $E[R]_\rho$.

Proposition 1. *The expected revenue for delivering one unit of food in marketing period 2, $E[R]$, decreases with respect to the probability that food is safe, ρ, when 1) the confidence effect is small compared to the quantity effect so the price in the second marketing period increases with respect to k and 2) the degree of traceability is large so the farms can secure revenue even when k is large.*

Proof: See appendix A.

For $E[R]_\rho$ to be negative, the price when k is large must be high compared to the price when k is small. This happens when the confidence effect is small compared to the output effect. Moreover, the degree of traceability must be sufficiently large such that the likelihood that a farm is paid when k is large is also high. The role of traceability is to secure revenue for a farm in period 2 when other farms delivered unsafe food in marketing period 1. Still, because $T \in [T_{\min}, 1)$, the larger the number of farms delivering unsafe food, the less likely it is that a farm delivering safe food will be paid in marketing period 2.

Let us now turn to the comparison of an industry organization choice of food safety and individual farms choice of food safety. Proposition 2 compares the choice of food safety by farms acting independently to the choice of food safety by an industry organization that maximizes the collective industry profit.

Proposition 2. *A) If $E[R]_{\rho} > 0$ when evaluated at ρ^F, the profit maximizing level of food safety for individual farms is smaller than the profit maximizing level of food safety for the industry acting together, $\rho^F < \rho^I$. B) Conversely, if $E[R]_{\rho} < 0$ when evaluated at ρ^F, the profit maximizing level of food safety for farms acting individually is larger than the profit maximizing level of food safety for the industry acting as a group, $\rho^F > \rho^I$.*

Proof: See appendix A.

Part A) of proposition 2 highlights a potential industry public good issue for the safety of food. Each farm contributes to maintaining the general reputation of the industry by delivering safe food. If the industry cannot enforce its level of food safety, individual farms choose a level of food safety that is low compared to what is optimal for the industry. For part A) of proposition 2 to hold, buyers must react relatively strongly in the second marketing period to the discovery of contaminated food in the first period such that safe farms do not benefit from food safety events. As a consequence, farms do not sufficiently internalize the effect of supplying unsafe food on the other farms.

Part B) of proposition 2 states that individual farms may supply too much food safety compared to what is profit maximizing for the industry collective. In such circumstances, the industry benefits from unsafe food being removed in marketing period 2. This is equivalent to the industry exercising a kind of market power.[22] Of course, individual farms want their own product to be safe but gain revenue when the product of some other farms is found to be unsafe. Thus, an industry agreement to maintain relatively loose food safety standards may be accepted by the group but individual farms have a incentive to adopt a higher standard than the agreed industry standard. A firm that adopts higher standards would be more likely to remain in the market when a food safety incident occurs and prices rise.

[22] We assume that the number of farms, which is also the quantity of food in the first period, is large enough such that the total quantity of food marketed is larger than the profit maximizing quantity for a cartel. This implies that the removal of food increases the total revenue of the industry if the confidence effect is zero.

Obviously, the explicit and public encouragement of unsafe food as a volume control mechanism would be difficult to justify by an industry organization. Part B) of proposition 2 acknowledges that in some cases an industry may benefit from unsafe food. It does not suggest that we would observe an industry organization explicitly seeking to reduce the safety of food to achieve volume control.[23] However, we often observe industries resisting governmental regulations designed to increase food safety.

Effects of increased traceability on the safety of food

In this section, we examine the effects of an exogenous increase in traceability on the safety of food chosen by individual farms or by an industry organization. The increase in the degree of traceability can be set by the industry organization, or mandated by the government or induced by a change in technology. We assume throughout that background traceability, $T_{\min}$, is achieved at zero costs to farms.

Effects of increased traceability on individual farms' choice of food safety

To derive the effect of an exogenous increase in the degree of traceability on the profit maximizing level of food safety for farms acting individually, take the total differential of the first order condition for profit maximization given by (8), holding constant the number of farms

$$(12)\quad E[R]_{\rho} d\rho^{F} + E[R]_{T} dT - 2C_{\rho,\rho} d\rho^{F} - C_{\rho,T} dT = 0,$$

[23] An industry organization can achieve volume control with better instruments than the safety of food. Volume control schemes are common in agriculture. In the United States, some federal marketing orders allow volume control practices. See Lee et al. (1996) for a review of California marketing programs. In Canada, the production of milk, poultry and eggs are under supply management. The incidence of volume control on surplus is the subject of a voluminous literature (see for example Seagraves 1969; Sumner and Wolf 1996).

where $C_{\rho,T} \equiv \partial^2 C(\rho,T)/\partial\rho\partial T$. Here, for simplicity, we assume that $C_{\rho,T} = 0$. Traceability systems are generally recordkeeping methods that do not influence the cost of sanitation or other food safety measures.[24]

In evaluating (8), $E[R]_{\rho_i} = 0$ because $E[R]$ is not a function of ρ_i. However, in (12), when performing comparative statics on (8), the partial derivative of the expected revenue with respect to the probability that food is safe does not equal zero because the displacement considers that all farms are identical, i.e $\rho_i = \rho^F \forall i$. Recall that the sign of $E[R]_\rho$ is the subject of proposition 1.

The partial derivative of the expected revenue when food is safe with respect to traceability is given by

$$(13)\quad E[R]_T = \sum_{k=1}^{N-1} \binom{N-1}{k} \rho^{N-1-k}(1-\rho)^k k T^{k-1} P[(N-k), s(k)].$$

More traceability increases the probability that a food safety incident is isolated, thereby leading to a higher expected revenue in the second marketing period, that is $E[R]_T > 0$.

Solving (12) for the change in the profit maximizing level of food safety for farms with respect to a change in the degree of traceability yields

$$(14)\quad \frac{d\rho^F}{dT} = \frac{-E[R]_T}{E[R]_\rho - 2C_{\rho,\rho}}.$$

As shown above, $E[R]_T$ is always positive, which implies that the numerator in (14) is always negative. Thus the sign of (14) depends only on the sign of the denominator.

From the denominator of (14), the profit maximizing level of food safety for individual farms increases when $E[R]_\rho < 2C_{\rho,\rho}$. This condition is satisfied when $E[R]_\rho$ is negative or when $E[R]_\rho$ is positive but small compared to $2C_{\rho,\rho}$. Analogously, the profit

[24] In the case where increased traceability requires that farms segregate batches of product and sanitize their equipment between batches, the cost of food safety and traceability may not be independent.

maximizing level of food safety for individual farms decreases when $E[R]_\rho > 2C_{\rho,\rho}$. The condition can only be satisfied when $E[R]_\rho$ is positive.

Let us consider how the denominator in (14) behaves as ρ^F approaches 1.0. First, $E[R]_\rho$ is positive but relatively small because $E[R]$ tends toward $P[N,d(0)]$ as ρ approaches 1.0. However, $C_{\rho,\rho}$ is large because it is not possible to make all food safe such that the cost function has an asymptote at $\rho = 1.0$. This implies that the denominator in (14) is negative and the level of food safety chosen by farms increases with respect to an increase in the degree of traceability.

Effects of increased traceability on an industry collective choice of food safety

Next, let us consider the effect of increased traceability on the profit maximizing level of food safety for the industry when farms are able to set food safety standards collectively. We start by taking the total differential of the first order condition for profit maximization with respect to the safety of food given by (9), holding the number of farms constant

$$(15)\quad 2E[R]_\rho d\rho^I + E[R]_T dT + \rho E[R]_{\rho,\rho} d\rho^I + \rho E[R]_{\rho,T} dT - 2C_{\rho,\rho} d\rho^I - 2C_{\rho,T} dT = 0,$$

where $E[R]_{\rho,T} \equiv \partial^2 E[R]/\partial\rho\partial T$. Again, for simplicity, we assume that $C_{\rho,T} = 0$.

Solving (15) for the change in the profit maximizing level of food safety for the industry collective with respect to a change in the degree of traceability yields

$$(16)\quad \frac{d\rho^I}{dT} = \frac{-(\rho E[R]_{\rho,T} + E[R]_T)}{2E[R]_\rho + \rho E[R]_{\rho,\rho} - 2C_{\rho,\rho}}.$$

The denominator is negative from the second order condition given by (11). Thus, the sign of $d\rho^I/dT$ depends on the sign of the numerator. When $\rho E[R]_{\rho,T} + E[R]_T > 0$, ($E[R]_{\rho,T}$ can be positive or negative) the profit maximizing degree of food safety for the industry increases with respect to increased traceability, that is $d\rho^I/dT>0$. When $\rho E[R]_{\rho,T} + E[R]_T < 0$, the profit maximizing degree of food safety for the industry decreases with respect to the degree of traceability, that is $d\rho^I/dT < 0$.

Comparison of the effects of traceability on food safety

Proposition 2 shows that farms acting individually choose less food safety than farms acting collectively when the confidence effect dominates the quantity effect. In this case, the industry organization may have difficulties in enforcing a designed food safety standard.

Moreover, proposition 2 shows that the profit maximizing level of food safety for farms acting individually is larger than that of the industry collective when the quantity effect dominates the confidence effect. Of course, it is not like any industry organization would explicitly limit the safety efforts chosen by its members. However, an industry organization could encourage traceability so that individual farms will choose lower levels of food safety.

Proposition 3 says that an industry organization may be able to induce farms to increase the safety of their food toward to the level set by industry collective action when $\rho^F < \rho^I$. However, when farms acting individually over-supply food safety compared to the industry acting collectively, increased traceability does not induce individual farms to choose a level of food safety that is closer to the profit maximizing level of food safety for the industry collective.

Proposition 3. *If food safety regulation is not binding and $\rho^F < \rho^I$, increased traceability induces farms to deliver safer food. Furthermore, in such case, the profit maximizing safety of food for farms acting individually may approach the profit maximizing of level food safety for the industry collective. If food safety regulation is not binding and $\rho^F > \rho^I$, then the industry organization* cannot *induce its members to deliver food that is less safe by increasing the traceability of food.*

Proof: See appendix A.

Proposition 3 suggests that food traceability can play a limited role for an industry organization to induce individual farms to spend resources to achieve a food safety level that is closer to the profit maximizing level of food safety for the industry collective. However, proposition 3 says that the industry organization cannot use traceability to induce individual farms to lower the safety of their food in order to exert volume control.

Augmented traceability may increase expected profits albeit not allowing the industry organization to adjust the level of food safety. We examine the profit maximizing degree of traceability for the industry collective in the next section.

Profit maximizing degree of traceability for the industry as a whole

Unlike earlier sections, here we consider endogenous traceability. We analyze the conditions under which the industry organization will augment the degree of traceability given that augmented traceability induces changes in food safety.[25] We first derive the profit maximizing degree of traceability when the industry organization can set both the safety of food and the degree of traceability. Then, we show the profit maximizing degree of traceability for the industry collective when the safety of food is set by individual farms. In both cases, we assume that before the intervention of the industry organization that traceability equals $T_{\min}$.

Profit maximizing traceability when the industry organization sets the safety of food

Assume that the industry organization is able to enforce a minimum level of food safety. The first order condition for the maximization of profit for the industry collective with respect to the degree of traceability is given by

$$(17)\quad \frac{\partial E[\Pi]}{\partial T} = \rho E[R]_T - 2C_T.$$

[25] Here, we do not consider the degree of traceability desired by individual farms lobbying for traceability. It would differ from the industry collective desired degree of traceability because individual farms do not internalize the quantity effect.

The first order conditions for the maximization of profit for the industry collective with respect to the safety of food, expression (9), and with respect to the degree of traceability, expression (17), together define the profit maximizing level of food safety and the profit maximizing degree of traceability for the industry collective.

The industry organization does not augment the traceability of food when (17) is less than zero at $T_{\min}$. In that case, the marginal gains of increasing traceability, $\rho E[R]_T$, are smaller than the marginal costs of increasing traceability, $2C_T$.

If expression (17) is greater than zero at $T = T_{\min}$, the industry organization augments the degree of traceability until the marginal gains of increasing traceability $\rho E[R]_T$ equals the marginal cost of increasing traceability $2C_T$.

Profit maximizing traceability when individual farms set the safety of food

Proposition 3 states that when $\rho^F < \rho^I$, the industry organization may be able to induce farms to increase the safety of food by increasing the degree of traceability. However, proposition 3 also states that when $\rho^F > \rho^I$ the industry organization is not able to induce farms to reduce the safety of food by increasing traceability. Here, we show how the induced change in the profit maximizing level of food safety for individual farms affects the degree of traceability that maximizes profits for the industry collective.

The industry organization knows how a change in the degree of traceability affects farms' choice of food safety and therefore sets the degree of traceability to maximize the industry profit accordingly. The first order condition for the industry profit maximization is

$$\begin{aligned}\frac{\partial E[\Pi]}{\partial T} &= \rho E[R]_T - 2C_T + \rho E[R]_\rho \frac{\partial \rho^F}{\partial T} - (E[R] - 2C_\rho)\frac{\partial \rho^F}{\partial T} \\ &= \rho E[R]_T - 2C_T + \rho E[R]_\rho \frac{\partial \rho^F}{\partial T} \qquad (18)\end{aligned}$$

because $E[R] - 2C_\rho$ equals zero from the first order condition for profit maximization by individual farms given by (8). Expression (18) equals zero for the interior solution.

When individual farms choose the level of food safety, the degree of traceability chosen by the industry organization is influenced by the induced change in ρ^F. In (18), this is apparent because the term $\rho E[R]_\rho(\partial\rho^F/\partial T)$ does not equal to zero.

Clearly, the industry organization does not seek to increase the traceability of food if (18) is smaller than zero when evaluated at $T_{\min}$. In such case, the net marginal gains from increased traceability are negative or the net marginal gains are positive but are totally offset by the change in the profit maximizing level of food safety for individual farms.

Proposition 3 shows that increased traceability does not cause ρ^F to approach ρ^I when $\rho^F > \rho^I$. Still, the industry organization may augment the degree of traceability but the net marginal gains from increased traceability are partially offset because the product of $d\rho^F/dT$ and $E[R]_\rho$ is negative (see proposition 2 and proposition 3).

Proposition 4 shows that when individual farms pick ρ, the induced change in the safety of food from increased traceability may cause the industry organization to augment the degree of traceability beyond what it chooses when it also chooses ρ.

Proposition 4. *The industry organization increases the traceability of food beyond the equality of* $\rho E[R]_T$ *and* $2C_T$ *(see equation* (17)*) if and only if: A) the level of food safety chosen by individual farms is smaller than the profit maximizing level of food safety for the industry organization,* $\rho^F < \rho^I$*, and B) augmented traceability induces individual farms to increase the safety of food,* $\partial\rho^F/\partial T > 0$*.*

Proof: See the appendix A.

The product of $E[R]_\rho$ and $\partial\rho^F/\partial T$ must be positive for the induced change in food safety to cause the industry organization to augment the degree of traceability beyond the equality of the marginal gains from traceability and the marginal cost of traceability such that $E[R]_T < 2C_T$. Proposition 4 says that this can only happen when $\rho^F < \rho^I$ and $\partial\rho^F/\partial T > 0$.

The results of proposition 3 and proposition 4 taken together provide additional insights. Only when increased traceability induces the profit maximizing level of food safety for individual farms to approach the profit maximizing level of food safety for the industry collectively will the industry organization seek to increase the traceability of food beyond the equality of $\rho E[R]_T$ and $2C_T$. When the industry organization cannot control food safety itself, it may choose more T than otherwise (or to implement a new traceability system). This only happens when more traceability causes the farm-chosen level of food safety to approach the industry-chosen level of food safety.

Summary and conclusions

This article focuses on situations in which farms act collectively (directly or through government regulation) to impose a traceability system on their industry in order to limit the scope of food safety incidents that would otherwise affect a large group of farms. Examples of industries adopting traceability to protect their reputation include California strawberries and California cantaloupes. Other recent examples include the efforts that have been undertaken by the U.S. and the Canadian cattle industries to implement identification and traceability systems.

In this article, increased traceability protects the reputation of an industry from randomly occurring food safety incidents by isolating the product from farms that were the source of the problem. The expected revenue of a farm depends on the probability that other farms have delivered unsafe food in an earlier period, the probability that unsafe food is traced to its origin, and the reaction of buyers to the discovery of unsafe food. Increased traceability changes the incentives for individual farms to supply safe food. The sign of the induced change in safety depends on how much the confidence of buyers is shaken by the announcement that unsafe food has been found compared to the price gain caused by reduced quantities in the market.

We derive four main results. First, we show that the expected revenue of a farm for delivering safe food may decrease when food is made safer. This is possible when buyers react mildly to food safety incidents (small confidence effect) while the price of food increases substantially when less food remains on the market (large quantity effect).

Second, as a consequence of the first result, the profit maximizing level of food safety for individual farms does not equal the profit maximizing level of food safety for the industry acting collectively. The level of food safety chosen by individual farms may be higher than the level of food safety that would be optimal for an industry organization. As opposed to individual farms, the industry organization takes into account the price impacts of reduced quantity of product remaining on the market when unsafe food is detected and removed. The model incorporates the fact that the industry collectively may benefit from food safety problems of some suppliers when consumers react mildly to discoveries of unsafe food.[26] Conversely, when the confidence of consumers is more sensitive to food safety lapses, the profit maximizing level of food safety for individual farms is lower than the profit maximizing level of food safety for the industry collectively.

Third, we show that whereas an industry organization may use traceability to encourage food safety, it cannot increase industry profits by strategically using traceability to induce farms to reduce food safety. We show that in such a case increased traceability induces individual farms to augment food safety above the level that would be chosen collectively and thus traceability would not be pursued by an industry organization.

Fourth, the induced change in food safety from increased traceability may cause the industry organization to increase investments in traceability by more when farms individually under-supply food safety. The industry organization may still want to in-

[26] Of course, as emphasized above, we do not claim that industry organizations would explicitly use food safety as a volume control device.

crease the degree of traceability when individual farms over-supply food safety. However, in such a case, the profit gains from better traceability are partially or totally offset by the loss in profit from induced changes in the safety of food.

Our model can be applied to explore a number of food safety issues. For instance, country of origin labeling may offer a sufficient degree of traceability to protect the reputation of the home country if a food safety incident originates from an imported food product. The results presented in this article suggest that home farms may benefit from an incident originating in the foreign country if the confidence of consumers in the safety of the home product is not significantly affected by the safety induced ban of the foreign product.

Other potential applications include analysis of the interaction between traceability and collective minimum quality standards. For example, when wines are labeled with a particular region designation, a minimum share of grape must originate from that region. Wineries that enjoy a positive collective reputation associated with a high-quality region have incentives to substitute grapes from other regions. *Ex post* testing of the origin of grapes is difficult. A traceability system is used to verify the origin of grapes and punish wineries that misrepresent the origin of their grapes. Our results extend directly to collective action and related incentives in this context.

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Appendix A: Proofs

This appendix provides the proofs to the propositions in the text.

Proof of proposition 1

The partial derivative of the expected revenue for a farm that delivers safe food with respect to the probability that another farm j supplies safe food is given in the text by (10). The last multiplicative term in (10), $\frac{(N-1)(1-\rho)-k}{\rho(1-\rho)}$, is positive for k smaller than $(N-1)(1-\rho)$ but negative for k larger than $(N-1)(1-\rho)$. The sign of $E[R]_\rho$ is positive or negative depending on the weight given by $\rho^{N-1-k}(1-\rho)^k T^k P[(N-k), d(k)]$ for each k to in the term $\frac{(N-1)(1-\rho)-k}{\rho(1-\rho)}$ since (10) is a weighted sum.

To identify the effect of traceability and the price of food on $E[R]_\rho$, consider first a case where food is always traceable, $T = 1$, and that the price is constant and equal to 1, $P[.] = 1$ for every k. This assumption implies that the confidence effect and the quantity effect offset each other and that the weight given to positive and negative values of $\frac{(N-1)(1-\rho)-k}{\rho(1-\rho)}$ is not affected by the price or by traceability. Under these assumptions, expression (10) simplifies to $E[R]_\rho = 0$. This means that a necessary condition for $E[R]_\rho$ to be negative is that the weight given to negative values by $T^k P[(N-k), d(k)]$ for $k > (N-1)(1-\rho)$ must be larger in absolute value than the weight given to positive values by $T^k P[(N-k), d(k)]$ for $k < (N-1)(1-\rho)$. Thus, $T^k P[(N-k), d(k)]$ must be an increasing function of k.

A necessary condition for $T^k P[(N-k), d(k)]$ to be an increasing function of k is that the quantity effect dominates the confidence effect such that $\partial P[(N-k), d(k)]/\partial k > 0$. Therefore, the first condition for $E[R]_\rho < 0$ is that the quantity effect dominates the confidence effect. T^k is a decreasing function of k because $T \in [T_{\min}, 1)$. However, $\partial^2 T^k/\partial k \partial T > 0$ as T is close to 1. Consequently, a large degree of traceability contributes to $E[R]_\rho < 0$, giving the second condition that T is close to 1.□

Proof of proposition 2

A) At $\rho = \rho^F$, (8) must hold such that $E[R] - 2C_\rho = 0$. But if $E[R]_\rho > 0$, (9) cannot hold when evaluated at ρ^F. Since expression (9) defines ρ^I, it implies that $\rho^F \neq \rho^I$ because $E[R]_\rho > 0$. For expression (9) to hold, $\rho^I > \rho^F$ such that $E[R] - 2C_\rho < 0$ because $E[R]_\rho > 0$. B) The proof is analogue to the proof of part A).□

Proof of proposition 3

First, we show that $E[R]_\rho < 0$ is a sufficient but not necessary condition for $E[R]_{\rho,T} < 0$. The expression for $E[R]_{\rho,T}$ is given by

$$\text{(A.1)} \quad \frac{\partial^2 E[R]}{\partial\rho\partial T} = \frac{1}{T}\sum_{k=0}^{N-1}\binom{N-1}{k}\rho^{N-1-k}(1-\rho)^k T^k P[(N-k),d(k)]k\frac{(N-1)(1-\rho)-k}{\rho(1-\rho)}.$$

Following the argument in the proof of proposition 1, the sign of $E[R]_{\rho,T}$ is determined by the sign of the last multiplicative argument $k\frac{(N-1)(1-\rho)-k}{\rho(1-\rho)}$. Comparing (A.1) to (10), the condition for $E[R]_{\rho,T} < 0$ is weaker than the condition for $E[R]_\rho < 0$ because k multiplies the effects of traceability and the prices, giving more weight to negative values that occur when k is large. Thus, $E[R]_\rho < 0$ is a sufficient condition for $E[R]_{\rho,T} < 0$. Again, because more weight is given to negative values in the expression for $E[R]_{\rho,T}$ compared to the expression for $E[R]_\rho$, $E[R]_{\rho,T}$ can be negative even though $E[R]_\rho$ is positive. Thus, $E[R]_\rho < 0$ is not a necessary condition for $E[R]_{\rho,T} < 0$. Using this result to sign (16), the sign of the change in the profit maximizing level of food safety for the industry collective when $E[R]_\rho\Big|_{\rho=\rho^F} < 0$ cannot be determined.

From proposition 1, we know that if $E[R]_\rho\Big|_{\rho=\rho^F} > 0$ then $\rho^F < \rho^I$. Thus, if $E[R]_\rho > 0$ but small compared to $2C_{\rho,\rho}$ such that $E[R]_\rho - 2C_{\rho,\rho} < 0$, (14) shows that the profit maximizing level of food safety of individual farms increases with respect to traceability. However, (16) says that ρ^I also increases with traceability. Therefore, if the profit maximizing level of food safety for individual farms increases more rapidly than the profit maximizing level of food safety for the industry collective, that is $d\rho^F/dT > d\rho^I/dT$, ρ^F moves closer to ρ^I with increased traceability.

Proposition 1 states that if $E[R]_\rho\Big|_{\rho=\rho^F} < 0$, then $\rho^F > \rho^I$. Expression (14) shows that when $E[R]_\rho\Big|_{\rho=\rho^F} < 0$, the profit maximizing level of food safety for individual farms increases with respect to increased traceability. Thus, the industry organization cannot induce farms to deliver less safe food by increasing the traceability of food when $\rho^F > \rho^I$.□

Proof of proposition 4

The induced change in the safety of food chosen by the individual farms causes the industry organization to increase food traceability beyond the equality of $E[R]_T$ and $2C_T$ if and only if the product of $E[R]_\rho$ and $\partial\rho/\partial T$ is positive.

Proposition 2 says that $E[R]_\rho < 0$ implies that $\rho^F > \rho^I$. However, as shown in the discussion below expression (14), $E[R]_\rho < 0$ also implies that $d\rho^F/dT > 0$. Thus, the product of $E[R]_\rho$ and $\partial\rho/\partial T$ is always negative when $\rho^F > \rho^I$.

Proposition 2 also says that $E[R]_\rho > 0$ implies that $\rho^F < \rho^I$. However, as shown in the discussion below expression (14), the sign of $d\rho^F/dT$ when $E[R]_\rho > 0$ depends on the sign of $E[R]_\rho - 2C_{\rho,\rho}$. If $E[R]_\rho < 2C_{\rho,\rho}$, it implies that $d\rho^F/dT < 0$ such that the product of $E[R]_\rho$ and $\partial\rho/\partial T$ is smaller than zero. Nevertheless, if $E[R]_\rho > 2C_{\rho,\rho}$ it implies that $d\rho^F/dT > 0$ such that the product of $E[R]_\rho$ and $\partial\rho/\partial T$ is greater than zero.□

Appendix B: The case of imperfect traceability

In the text, we assume that traceability is accurate in the sense that no unsafe food is traced to the wrong farm. In this appendix, traceability is not always accurate. When a food safety incident occurs in marketing period 1 and traceability is applied, the farm identified may not be the correct one. We still measure traceability as the probability that the farm of origin is reported. The probability that the correct farm is reported is given by T_0. The probability that the wrong farm is reported is given by T_1. The probability that no farm of origin is reported when one unit of unsafe food is detected is given by $1-T_0-T_1$.

Introducing errors in the traceability of food affects the expected revenue in marketing period 2. Here, for simplicity, we consider a case where there are only two farms. Rewriting (6) for the two farms case using the modified definition of traceability, the expected revenue in marketing period 2 for a farm that delivers safe food in marketing period 1 is given by

$$\begin{aligned} E[R_i|S_i=1] &= \rho P[2,d(0)] + (1-\rho)(T_0 P[1,d(1)] + T_1\times(0) + (1-T_0-T_1)\times(0)) \\ &= \rho P[2,d(0)] + (1-\rho)T_0 P[1,d(1)]. \end{aligned} \tag{B.1}$$

In (B.1), the term $(1-\rho)T_1\times(0)$ represents the case that farm j fails to deliver safe food but that farm i is incorrectly reported as the source of the tainted product. With probability $1-T_0-T_1$, the traceability system fails to provide the origin of the contaminated product, accurately or not, and no farm is paid.

When a product is traced to the wrong farm, a farm may be paid in marketing period 2 even though it delivered unsafe food in marketing period 1. The expected revenue to farm i in marketing period 2 when it delivers unsafe food in marketing period 1 simplifies to

$$\begin{aligned} E[R_i|S_i=0] &= \rho(T_0\times(0) + T_1 P[1,s(1)] + (1-T_0-T_1)\times(0)) + (1-\rho)\times(0) \\ &= \rho T_1 P[1,s(1)]. \end{aligned} \tag{B.2}$$

Thus, when unsafe food originates from farm i but is traced to farm j, farm i is paid in marketing period 2 as if it had delivered safe food.

We can now write the expected revenue of a farm in marketing period 2 when traceability may fail to report the correct farm of origin. Using (B.1) and (B.2) in (2) yields

$$\begin{aligned} E[R_i|S_i] &= \rho E[R_i|S_i=1]+(1-\rho)E[R_i|S_i=0] \\ &= \rho(\rho P[2,d(0)]+(1-\rho)T_0P[1,d(1)])+(1-\rho)\rho T_1P[1,s(1)] \\ &= \rho^2P[2,d(0)]+\rho(1-\rho)(T_0+T_1)P[1,d(1)]). \end{aligned}$$

Writing $T=T_0+T_1$, we find that allowing for errors in tracing the origin of food does not affect the expression for the expected revenue of a farm in marketing period 2. This example with two farms can be generalized to the case of N farms.