Economically Motivated Adulteration in Farming Supply Chains: The Role of Supply Chain Dispersion and Traceability

Food adulteration is one of the leading causes of health risks around the world and particularly in developing countries like China. Food adulteration could be the result of unintentional negligence or incompetence such as the case of bacterial contamination due to bad hygiene practices. However, many incidents of food adulteration are intentional and are motivated by malicious intentions (e.g., bioterrorism) or by financial motives. The latter is often called economically motivated adulteration (EMA). Over the last several decades there were many incidents of EMA of food around the world and in particular in China. For example, consumption of melamine-tainted infant formula and milk led to six infant deaths and nearly 300,000 young children severely sickened in China in 2008 (Everstine et al. 2013). In another example the outbreaks of avian flu in China has led to extensive use of antibiotics and other illegal drugs in poultry farming in China. In particular, in 2012, the KFC “Instant Chicken Scandal” in China revealed that the chickens used by KFC were fed with as many as 18 antibiotics on the farms (Pi et al. 2014).

Ample case-studies and qualitative research highlight various factors that could affect the motivation and ability of farmers to engage in EMA. Quality uncertainty or variability is hypothesized to be a major cause of EMA especially in markets with quality-based prices. For example, the intentional contamination of milk with melamine in China emerged in response to price pressure for high-protein milk that led farmers and dealers to use melamine to increase the perceived protein level. Similar situation emerged in India’s dairy supply chain where farmers were found adulterating milk with urea to increase its SNF content. These two examples relate to reactive EMA, in which farmers react to quality gap and variability. On the other hand, the use of antibiotics in the poultry farming supply chain in China emerged as a preemptive EMA, in which fear from producing low-quality chickens (e.g., sick or underweight) prompted farmers to extensively use antibiotics. Other factors that were hypothesized in the literature to affect EMA in farming supply chains are traceability (i.e., the ability to track back adulteration to the source), inspection accuracy, and supply chain structure, particularly how dispersed the supply chain is. The latter is especially significant in developing countries in which the agriculture system often rely on many small household farmers (Huang et al. 2017).

In this paper, we develop a game-theoretic analytical model to study the effects of all of these factors on preemptive and reactive EMA behaviors in farming supply chains. Unlike existing work that is primarily anecdotal and focused on one aspect, the model we develop captures all of these aspects and allows us to study their interactions. We leverage the analysis of the model to derive important and surprising insights that can inform both policy makers and commercial entities in food supply chains to address EMA risks. Moreover, we use real data from case studies to calibrate our model and highlight its ‘predictive’ power.
**Modeling approach.** Next, we provide a high-level description of the modeling approach and how it is motivated. We consider a single manufacturer procuring a fixed number of agricultural products from a network of homogeneous farmers. By keeping the total procurement constant and changing the number of farmers we are able to study the effect of supply chain dispersion on the risk of EMA. The sequence of events for the preemptive adulteration scenario is as follows: (i) Farmers decide the amount of adulterants to add to decrease the likelihood of producing low-quality supplies. (ii) The uncertain quality of the supplies is realized. (iii) Each farmer is paid based on the average quality of his supply. (iv) The manufacturer stores samples from some farmers and mixes the supplies from all of the farmers. (v) With some probability, the manufacturer tests the mixed supply for adulterants. If adulterants are detected in the mixed supply, then the manufacturer tests each of the stored samples for adulterants. (vi) If adulterants are detected in a farmer’s sample, then the farmer is charged a penalty. For the reactive adulteration scenario, the only difference in the sequence of events occur in the first two steps. That is, the uncertain quality of each farmer’s supply is first realized, and then the farmer decides whether or not to adulterate the low-quality supplies to create fake high-quality ones. The remaining steps remain the same as in the preemptive adulteration scenario. A farmer’s objective is to maximize his final expected payoff after accounting for possible penalty if he chooses to adulterate and is caught by the manufacturer.

We next explain steps (iii)--(vii) in our model dynamics in more detail. First, we model quality-based pricing in step (iii), which is a very common payment scheme in many agricultural industries. The price difference between high- and low-quality products is an important economic motive for farmers to engage in adulteration. Second, we capture the traceability of the supply chain by modeling the number of samples stored by the manufacturer in step (iv). In a fully traceable supply chain, each farmer’s sample is stored and hence, can be tested later for adulterants if needed. Conversely, in a partially traceable supply chain only some of the farmers’ samples will be stored and tested if necessary. Third, in step (v), we model the manufacturer’s two-step quality inspection. Specifically, with some probability (which captures inspection frequency), the manufacturer tests the mixed supply for adulterants. Only if the mixed supply is found to have been adulterated will the manufacturer then test the stored samples. This two-step process is common in practice due to its cost effectiveness (Mu et al. 2016). We model two scenarios of testing accuracy for the manufacturer’s quality inspection: perfect testing and volume-based testing. Under perfect testing, any trace amount of adulterants can be detected in inspection. This scenario corresponds to the detection of well-known adulterants, for which advanced testing technologies have been established. Conversely, under volume-based testing, the chance of detecting adulteration is increasing in the amount of adulterants used in the supplies. Volume-based testing captures scenarios where adulteration is detected either through imperfect methods or due to illness outbreaks in the consumer population. For example, before the melamine-tainted infant formula scandal, raw milk was not tested for melamine directly (Chen et al. 2014). The scandal broke out only because the quantity of melamine added to the milk became so high that many children got ill, hence alerting the authorities.
**Results and insights.** Our analysis characterizes the game equilibrium in a range of scenarios under different assumptions with respect to supply chain dispersion, the level of tractability, and testing accuracy.

**Effect of supply chain dispersion on EMA risk:** Our analysis shows that in the majority of scenarios, supply chain dispersion increases EMA risks in the supply chain, both in the likelihood for an individual farmer to adulterate and in the expected total amount of adulterants present in the mixed supply. This result is in sharp contrast to the common recommendation in the current supply chain risk management literature that supplier diversification or multi-sourcing is desirable to establish supply chain resilience (Van Mieghem 2007, Tomlin 2009). We demonstrate that when risks come from endogenous forces (i.e., actions by an entity within the supply chain), as opposed to exogenous forces (e.g., earthquake, fire, hurricane) mostly studied in the literature, supplier diversification can be harmful.

**Effect of quality uncertainty on EMA risk:** Our analysis also highlights that investing in quality improvement without also improving the supply chain’s capability in quality inspection may backfire. This is because a lower chance of producing low-quality supplies can inadvertently motivate suppliers to endogenously adulterate the supplies (if possible) and create fake high-quality ones. Without the capability to differentiate fake high-quality products from truly high-quality ones, consumers could suffer from consuming adulterated products.

**Investing in traceability and dispersion to mitigate EMA risk:** Based on our analysis on the farmers’ strategic adulteration behavior, we examine the manufacturer’s optimal strategy for investing in supply chain traceability and inspection frequency to meet certain risk constraint while minimizing total investment costs. We find that the optimal cost is always increasing in dispersion. Further, if the manufacturer cannot satisfy the risk constraint even when she always inspects the mixed supply and the supply chain is fully traceable, then additional levers such as reducing supply chain dispersion would be necessary to meet the risk constraint.

**References**


