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Testing at the Source: Analytics-Enabled Risk-Based Sampling of Food Supply Chains in China

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Abstract. This paper illustrates how supply chain (SC) analytics could provide strategic and operational insights to evaluate the risk-based allocation of regulatory resources in food SCs, for management of food safety and adulteration risks. This paper leverages data on 89,970 tests of aquatic products extracted from a self-constructed data set of 2.6 million food safety tests conducted by the China Food and Drug Administration (CFDA) organizations. The integrated and structured data set is used to conduct innovative analysis that identifies the sources of adulteration risks in China's food SCs and contrasts them with the current test resource allocations of the CFDA. The analysis highlights multiple strategic insights. Particularly, it suggests potential gaps in the current CFDA testing allocation by SC location, which is heavily focused on retail and supermarkets. Instead, the analysis indicates that high-risk parts of the SC, such as wholesale and wet markets, are undersampled. Additionally, the paper highlights the impact that SC analytics could have on policy-level operational decision making to regulate food SCs and manage food safety. The hope is that the paper will stimulate the interest of academics with expertise in these areas to conduct more work in this important application domain.

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1. Introduction

Food safety and food adulteration are widespread problems that challenge regulatory bodies, the food industry, and consumers around the world. Managing food safety risks, such as foodborne illness outbreaks, or intentional and economically motivated adulteration (EMA) of food products is particularly difficult because of the size, complexity, and opaqueness of food supply chains (SCs). This challenge is underscored by the relatively scarce resources available to regulate and inspect these SCs. For example, each year the U.S. Food and Drug Administration (U.S. FDA) is able to sample only about 1%–2% of over 40 million imported food product lines (Racino 2011). China also faces major challenges in regulating its food system and mitigating food safety and EMA risks, particularly because of extremely disaggregated and complex food SCs. Indeed, China, like other countries, is experiencing major incidents of food adulteration. Perhaps the most notable case is the melamine incident, which caused multiple deaths and more than 50,000 babies to be hospitalized with serious injuries because of baby formula contaminated with melamine through the dairy SC in China.[1]

This paper provides a first of its kind analysis to illustrate how data-driven SC analytics can evaluate risk-based monitoring of food SCs to potentially identify gaps in the application of scarce regulatory resources. In particular, the paper focuses on China and leverages a unique, self-constructed data set of 2.6 million food safety tests collected from 60,000 files on 247 China Food and Drug Administration (CFDA) websites. This includes 1.8 million tests between 2014 and 2018, conducted in geographies where the data set is thought to comprehensively cover all public postings of the CFDA. Data on 89,970 tests of aquatic products are extracted from this larger data set, in order to provide both strategic and operational insights that could potentially inform *risk-based sampling* of food SCs in China (see Definition 1).

Definition 1. *Risk-based sampling* involves the use of data (e.g., historical sampling results) to identify points for testing (e.g., product categories, specific products, SC locations, companies) that are more likely to expose problems and their respective source.

This definition is analogous to risk-based approaches in healthcare, where qualitative and quantitative indicators are used to predict risk and considered as an input for intervention decisions (Iezzoni 2012). This is also consistent with the food sampling approach recently proposed by the China State Council, which plans to allocate more resources to high-risk product categories and companies (Xinhua News Agency 2019).

This paper provides a detailed analysis of the SC sources introducing detected adulterants in tests conducted by the CFDA. This provides strategic insights as to what are the high-risk SC locations (e.g., manufacturers) that require more regulatory attention. This is called *risk-based sampling by SC location*. Additionally, the paper provides operational insights by leveraging historical test results to identify *high-risk* companies that are more likely to introduce adulterants and therefore, should be prioritized for sampling. This is called *risk-based sampling of individual companies*.

Risk-based management of food SCs has also recently been recognized by the U.S. FDA as essential for food safety and in need of global adoption (U.S. Food and Drug Administration 2019). However, to the best of our knowledge, risk-based sampling of food SCs in China and other countries is not well developed, partially because of challenges to obtain, integrate, and operationalize relevant SC data. Thus, the unique data set that was developed and the corresponding analysis in this paper provide a first illustration of the promise of these approaches for enhancing regulatory management of food safety risks.

1.1. Paper's Contributions

The analysis in the paper relies on data of 89,970 tests of aquatic products extracted from an integrated, self-constructed data set of over 2.6 million food safety test results conducted by the CFDA throughout China, currently posted on over 60,000 files, with over 15,000 unique data schemas across 247 websites. Notably, because tests for specific product categories (e.g., aquatic products) are posted across all of these files and websites, this scale of data integration is necessary, and the size and quality of this integrated data set allow for a complexity of analysis not possible otherwise.

Leveraging this data set, the paper provides a novel SC risk source analysis for the freshwater aquatic product SC in China. This SC was chosen for several reasons. First, aquatic products are a high-risk food category with many incidents of adulteration (Fox et al. 2018). China is also the largest producer, exporter, and consumer of aquatic products worldwide (Xia 2019). Additionally, typical to China, this SC is also extremely complex and disaggregated, making risk-based management more important.

The SC risk source analysis considers 89,970 CFDA tests of aquatic products. Each failed test that detected specific adulterants is associated with the SC source (farming, environment, manufacturing, circulation) that was most likely to introduce the adulterant. The association is done based on expertise, technical and economic analysis of the underlying motivation to add the adulterants to the food, and where it would be most "likely" added. The result is an aggregated analysis of the sources of risk in the SC. Although the risk source analysis in this paper is focused on the freshwater aquatic SC in China, the insights are likely to hold more generally, and a framework to apply this approach to other food SCs is presented.

The main insight emerging from this analysis is that the major SC risk sources are farming and manufacturing, whereas the current CFDA policy results in more testing at retail/supermarkets. Moreover, an SC flow analysis shows that the vast majority of aquatic product supply, and the more risky part, is sold through wholesale markets (WSMs), wet markets, and restaurants rather than retail/supermarkets. The analysis suggests that these WSMs can potentially be leveraged to create a greater level of traceability in the SC. This insight is especially interesting in light of coronavirus disease 2019 (severe acute respiratory syndrome coronavirus 2), which is thought to have spread from the Wuhan Huanan Seafood Wholesale Market (Huaxia 2020). WSMs and wet markets in China have also been implicated in previous zoonotic disease outbreaks, such as severe acute respiratory syndrome and highly pathogenic Asian avian influenza A (H5N1) (Webster 2004).

The SC risk source analysis also provides operational insights to guide risk-based sampling of individual companies. Specifically, tests at retail/supermarkets are used to flag high-risk manufacturers, whose products failed because of an adulterant they are suspected to have introduced. The underlying hypothesis is that these types of flags should be considered when selecting manufacturers to be tested on-site, and the data are used for statistical support. Notably, the CFDA is not likely to be able to follow such a strategy at the moment because of the lack of data integration. This illustrates how risk-based sampling of individual companies could enhance the problem detection rate with the same level of resources.

Although more research is clearly needed to better understand important aspects related to developing an optimal regulatory strategy, there are many reasons to believe that the current policy could ultimately be improved by adapting more *risk-based sampling* and in particular, by increasing focus on WSMs, wet markets, and high-risk manufacturers. That said, the design of specific policies will have to consider and analyze various endogeneity issues that could create incentive problems if tests are reallocated (i.e., fewer tests at retail/supermarkets could result in more risk at those locations). Potentially, the CFDA could simply conduct more tests, with additional tests aimed at WSMs, wet markets, and high-risk manufacturers, thereby creating stronger incentives at those risky locations while not reducing incentives elsewhere.

The underlying theme of these insights is that data integration, SC analytics, and risk-based sampling could potentially enable a substantially more effective use of resources. The hope is that the paper will stimulate additional research by academics with SC and analytics expertise to further study food safety risks and better inform regulatory operations strategies and on the ground activities for the relevant authorities.

1.2. Related Work

Although this paper's risk-based approach to determine SC sources of adulteration is new, the work relates to existing literature in several ways. Other researchers have used the outcomes of public food safety tests to understand the overall state of food safety risk in China but with much more limited data than this paper. Notably, Liu et al. (2017) provide an overview of testing allocations, failures, and adulterant prevalence by product category for tests conducted by the central CFDA in 2016, and this work may be the only other academic research using public CFDA data to shed light on food safety risks. However, the work in this paper goes further by considering a substantially larger data set, covering provincial and prefecture data (see Section 2), and by conducting entirely different analyses emphasizing an SC perspective.

There are many studies on food safety risks based on incidents exposed by the news media. For example, Liu et al. (2015) report items causing food safety issues in a regional analysis focused on Beijing. Also, Liu et al. (2016) identify risks in the pork supply chain in China through news data. Although media exposure directly contributes to increasing public awareness of food safety, it contains insufficient information regarding many types of adulteration. In particular, this approach includes many acute instances of food poisoning but lacks data on adulterants with long-term impacts on health such as heavy metals. Such data might also include some censoring of incidents by reporters.

1.3. Outline

The rest of the paper is structured as follows. Section 2 describes the CFDA data set and integration process. Section 3 gives relevant background, including overviews of the food SC in China, and the current CFDA testing allocations and outcomes. Section 4 details the SC risk source analysis for the aquatic products and summarizes results. Section 5 discusses insights from these results and offers proposals for risk-based sampling by SC location and risk-based sampling of individual companies. Finally, Section 6 concludes.

2. Data

The paper relies on a self-constructed data set of food safety tests collected from all public postings of 247 CFDA organization websites, including the central CFDA, all 31 provinces, and 215 of the 334 prefectures.[2] This data set includes nearly all major cities and important agricultural areas (see Online Appendix EC.1 for a full list). Because CFDA organizations are mandated to publicly post all test results, as part of the China Food Safety Laws, it is reasonable to assume that these postings are relatively comprehensive.[3]

2.1. Data Integration

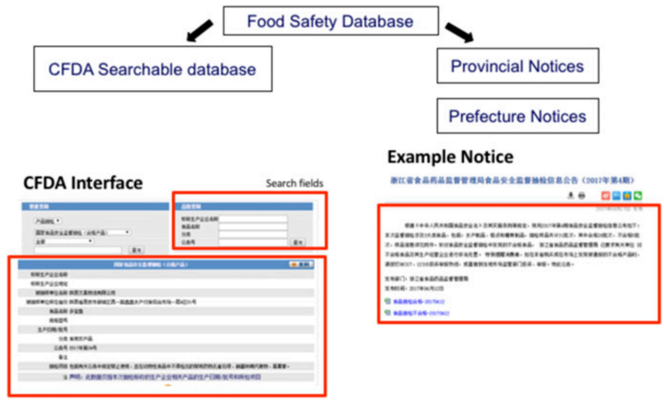
The central CFDA posts food safety tests on a searchable hypertext markup language (HTML) data set, with a single consistent format, whereas the prefecture and provincial CFDA organizations post their tests in a variety of formats, including embedded HTML tables, portable document format files (PDFs), and Microsoft Word/Excel files. Examples of the publicly posted data are shown in Figure 1.

Because the data are posted across 247 websites and include over 60,000 files with more than 15,000 unique data schemas, a manual approach to download, integrate, and process all of these relevant files is intractable in scope. Therefore, a semiautomated integration approach was created, shown in Figure 2.

2.2. Data Set Overview

A food safety test record typically includes information about what food was tested (food name and product category), where and when the sample was collected, the manufacturer, and the outcome (pass/fail and free text describing any adulterants causing failure). The analysis also relies on three structured features that were added to the data set. First, product category is only partially labeled in the raw data. A neural network is used to add product category for unlabeled data. Second, for failed tests, the detected adulterants are extracted from inspector notes using natural language processing. Third, the names and

Figure 1. (Color online) Food Safety Test Data Sources



addresses of the businesses being sampled are used to classify the corresponding SC location (e.g., restaurant, supermarket). More information about these structured variables is given in Online Appendix EC.2.

The final data set contains 2.6 million food safety tests. Restricting to tests conducted in the 215 prefectures for which all central-, provincial-, and prefecture-level data were integrated and removing the small number of publicly available tests conducted before 2014 (when public posting was not mandated by law) result in a data set of 1.8 million tests. This includes 89,970 tests of aquatic products, with an overall failure rate of 4.3%.

3. Background

This section gives relevant background, including an overview of China's food SCs, and the current CFDA testing allocations and outcomes.

3.1. The Food Supply Chain in China

Food SCs in China are often complex and differ substantially from those in most developed countries. Instead of most supply coming from large, vertically integrated commercial farms, China has 200 million mainly small and family-owned farms (Lowder et al. 2016). Figure 3 provides an overview of China's freshwater aquatic SC, which is typical for the complexity of food SCs in China. It was constructed through literature review (Ren and An 2010) and corroborated through interviews and field work.

As shown in Figure 3, there are two main regulatory agencies that oversee most food safety testing. The Ministry of Agriculture and Rural Affairs (MARA) is responsible for most testing at aquaculture farms, and the CFDA is responsible for most of the testing at upstream SC points.[4] Unlike the CFDA, the MARA does not post test results in the public domain. Therefore, the focus for the paper is on evaluating the CFDA testing strategy and outcomes in our analysis.

One important aspect from Figure 3 is the centrality of large WSMs, which are typically absent from food SCs in developed countries. WSMs specialize in a relatively small number of product categories and serve as consolidation points of the SC. Specifically, for aquatic products as well as many other product categories, WSMs consolidate 70%–80% of the total market supply (Chen et al. 2006). There are also just 4,500 large WSMs in China that sell food, and only some of which specialize in aquatic products.[5] For example, in Zhejiang province, whose population is 56 million, there are just 38 WSMs selling aquatic products.[6] The centrality of WSMs is particularly relevant for aquatic products because of Chinese consumer demand for live products from a variety of species and the extremely dispersed supply from small aquaculture farms.

Because of the centrality of WSMs, understanding outbound supply channels gives insight into how food typically reaches consumers. The channels for aquatic products WSM vendors were assessed through

Figure 2. Semiautomated Data Integration Pipeline

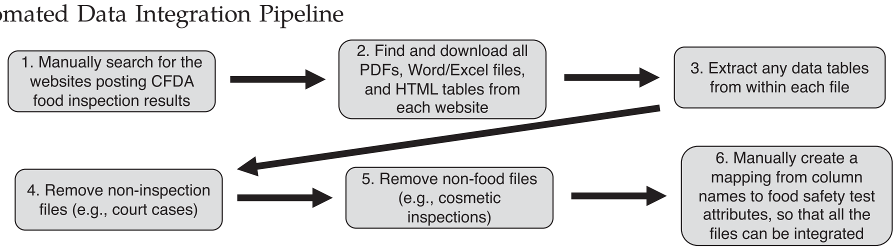
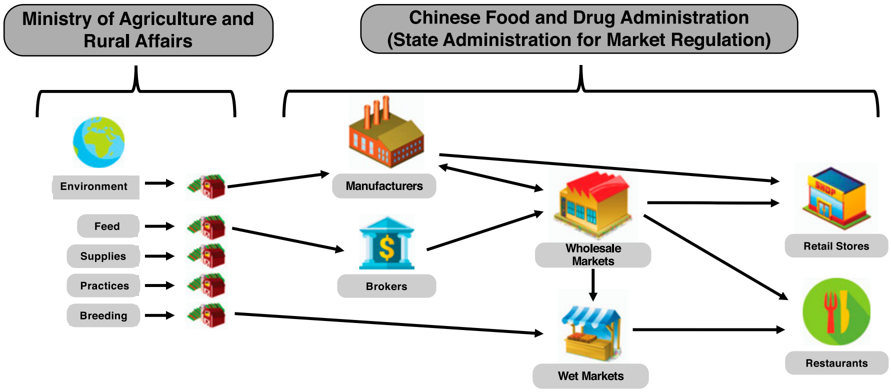


Figure 3. (Color online) The Freshwater Aquatic Supply Chain and Regulatory Agencies in China



a large-scale survey of vendors from all 76 aquatic products wholesale markets in Zhejiang and Hunan provinces (Jin et al. 2019). The supply of aquatic products, to each SC location from Figure 3, is shown in Table 1. More details related to this survey are given in Online Appendix EC.4.

Considering that 70%–80% of aquatic products are consolidated at WSMs, Table 1 implies that most aquatic products reach consumers through WSMs, smaller wet markets (similar to farmers' markets), and restaurants, without ever passing through a supermarket or retail store. These results were corroborated by discussions with experts, who believe wet markets are by far the most common purchase location for Chinese consumers, who tend to prefer live, fresh aquatic products.

Another important aspect to note from Figure 3 is that aquatic products will sometimes pass through as many as four SC locations before reaching the consumer. The various points in the SC represent separate business entities that may conceal sourcing for competitive advantage. This implies that testing in downstream locations makes it extremely hard, if not impossible, to trace back to the adulteration source, particularly if the adulteration source is farms.

3.2. Current CFDA Testing Strategy

The publicly stated CFDA testing strategy is to test broadly throughout the SC. However, in practice high proportions of tests are conducted at retail/supermarkets. Moreover, when food product test results are in violation of the regulations, the penalty (typically a fine) is levied only on the business where the test sample was taken from, unless there is documented traceability to the source of the adulteration.[7] This can be described as an *incentive-based* approach, where the government seeks to heavily incentivize retail/supermarkets to purchase from safe sources. A display of the CFDA's testing allocations and failure rates corresponding to different SC locations is presented in Table 2. This is constructed from the CFDA data set described in Section 2.

Table 2 shows that the CFDA allocates half its tests to retail/supermarkets, despite failure rates being lowest. A potential problem with this approach, at least for aquatic products, is that the majority of food passes from farms through wholesale and wet markets and then directly to the consumer or to small restaurants. As a result, there is less regulatory oversight for the typical sales path, and in fact, SC locations on this path carry more risky products. This is further supported by considering CFDA tests of agricultural products sourced from WSMs but conducted elsewhere. Such tests have a failure rate of 6.68% when conducted at restaurants and 3.33% when conducted at supermarkets (significant with two-sample binomial test), offering additional support that retail/supermarkets are indeed sourcing safer products from WSMs. These ideas are revisited in Section 5, which discusses major insights.

Table 1. WSM Customers by SC Location

Customer	Sales, %
Retail/supermarkets	6.39
Restaurants	9.83
Wet markets	62.55
Manufacturers	6.31
Household customers	14.92

4. SC Risk Source Analysis

This section considers failed tests of aquatic products in the CFDA data set described in Section 2. The goal of this analysis is to identify, for each failed test, the likely SC source that introduced the adulterant responsible for failure. For example, *sorbic acid* is a preservative sometimes added to dried aquatic products during the manufacturing/drying process. Therefore, the manufacturer is the most likely SC source adding sorbic acid. Another example is *malachite green*, an antimicrobial used to protect live, fresh fish

Table 2. All Products—CFDA Test Allocation and Failure Rates by SC Location

	All products, %		Aquatic products, %	
Sampled location SC type	Total tests	Failure rate	Total tests	Failure rate
Manufacturers	28.2	4.2	14.5	4.5
Restaurants	14.9	5.1	8.3	5.0
Retail/supermarkets	48.0	3.1	56.2	3.7
Wet markets	3.9	5.7	10.3	6.9
Wholesale markets	5.0	5.1	10.7	5.3
Total	100.0	3.9	100.0	4.4

from disease. Malachite green could be used either during the farming stages or during the circulation/transportation stages from farm to consumer. More generally, the idea is to identify the likely source based on analysis regarding where an adulterant could be added to the SC and where there would be incentives to add it.

Overall, the adulterants for aquatic products can be divided into four risk sources: farming, the environment (e.g., water pollution), manufacturing, and circulation, as shown in Figure 4. The ultimate goal of this section is to create an aggregated analysis regarding to what extent adulteration is introduced by each SC risk source.

4.1. Adulterant Risk Source Dictionary

To enable the risk source analysis, the mapping of adulterants to their likely SC sources, as done for *sorbic acid* and *malachite green*, is expanded for all adulterants that the CFDA tests for in aquatic products. The full mapping is shown in Table 3. These adulterants account for 75.2% of the failed tests of aquatic products in the data. The remaining failures were because of pathogen risk (19.1%), such as salmonella, and labeling issues (5.7%), both of which are excluded from the risk source analysis.[8] Table 3 also includes a high-level categorization of adulterants (e.g., lead is categorized as a heavy metal). Note that the likely SC risk source can vary within the same category (this is discussed more in Section 4.2).

Table 4 presents the proportion of failed tests from each adulterant category across tests conducted in the various SC locations.

4.2. Mixed Risk Sources

Although most adulterants in Table 3 are associated with a unique SC source, there are two categories associated with multiple SC sources. Specifically, certain heavy metals could be introduced from either environmental pollution or manufacturing, and certain antimicrobials could be introduced during either farming or circulation. For these cases, methodologies are developed to distinguish between the potential SC sources.

4.2.1. Heavy Metals. For aquatic products, the source of certain heavy metals could be either environmental pollution or manufacturing processes. However, for fresh (unprocessed) aquatic products in particular, the risk source cannot be manufacturing and therefore, must be environmental pollution. Records of aquatic products in the CFDA data set (see Section 2) are categorized as fresh if the food name includes only the species of the fish or shellfish along with a weight of the product. Records including words like "dried" or "salted" are categorized as processed.

Figure 4. (Color online) The Aquatic Products Supply Chain and the Four Risk Sources

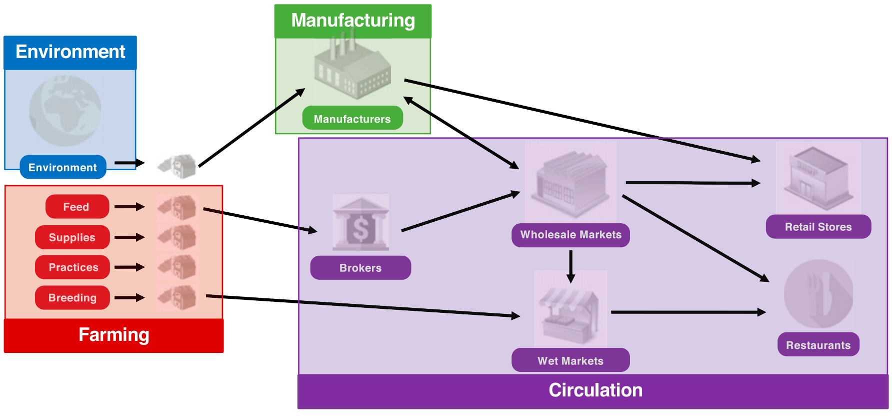


Table 3. Adulterant Risk Source Dictionary

Adulterant	Adulterant category	Risk source
Cadmium	Heavy metal	Environment/manufacturing
Lead	Heavy metal	Environment/manufacturing
Total/inorganic arsenic	Heavy metal	Environment/manufacturing
Enrofloxacin	Antimicrobial	Farming
Florfenicol	Antimicrobial	Farming
HMMNI	Antimicrobial	Farming
Metronidazole	Antimicrobial	Farming
Olaquindox	Antimicrobial	Farming
Oxytetracycline	Antimicrobial	Farming
Sarafloxacin	Antimicrobial	Farming
Sulfonamides	Antimicrobial	Farming
Chloramphenicol	Antimicrobial	Farming/circulation
Malachite green	Antimicrobial	Farming/circulation
Nitrofurans	Antimicrobial	Farming/circulation
Ponceau 4R	Food coloring	Manufacturing
Sunset yellow	Food coloring	Manufacturing
Tartrazine	Food coloring	Manufacturing
Aluminum	Heavy metal	Manufacturing
N-nitrosodimethylamine	Illegal food additive	Manufacturing
Benzoic acid	Preservative	Manufacturing
Butylated hydroxytoluene	Preservative	Manufacturing
Sorbic acid	Preservative	Manufacturing
Sulfur dioxide	Preservative	Manufacturing
Acesulfame potassium	Sweetener	Manufacturing
Saccharin sodium	Sweetener	Manufacturing
Sodium cyclamate	Sweetener	Manufacturing

HMMNI, hydroxy dimetridazole.

4.2.2. Antimicrobials. For aquatic products, the source of certain antimicrobials could be either farming practices or circulation. For the aggregated analysis, evidence from self-obtained testing data, a literature review, and interviews was used to attribute some percentage of this aggregate risk to farms and the remainder to circulation (Zhai et al. 2007, Fu et al. 2013). In particular, the following assumption was made.[9]

Assumption 1. *The proportion of antimicrobial risk coming from farms is in the interval* [62.3%, 97.5%] *for all testing locations.*

This assumption was formed using a 90% confidence Wilson score interval based on self-obtained testing data of blackfish and bream collected at wholesale markets in Zhejiang (Wilson 1927). For these tests, mass spectrometry was used to determine the amount of malachite green and its metabolite, leucomalachite green, present in failed tests. Using information about half-lives, it can be determined whether malachite green was used during farming or circulation. More information about these tests and the calculation of Assumption 1 is given in Online Appendix EC.3. Because malachite green is considered to be the most prevalent antimicrobial used in circulation and because the probability interval is quite wide, Assumption 1 is likely to be very conservative.

4.3. Results

Table 5 presents the results of the risk source analysis for aquatic products. The ranges are computed as follows. Each row corresponds to the respective SC location (e.g., restaurants, WSMs) and considers failed aquatic products tests conducted in that location. For each failed test, the risk source is determined based on Table 3. If the source is not uniquely assigned, then minimum and maximum probabilities are calculated based on the methodology described in Section 4.2.

Table 4. Adulterant Categories by Sampled Location SC Type

Sampled location SC type	Antimicrobial, %	Food coloring, %	Heavy metal, %	Illegal food additive, %	Preservative, %	Sweetener, %
Manufacturer	10.2	1.4	46.3	0.0	32.7	9.5
Restaurant	56.8	14.4	4.1	0.0	23.0	1.8
Retail/supermarket	55.0	3.4	16.9	0.4	23.6	0.7
Wholesale market	60.7	4.0	18.6	0.0	16.7	0.0
Wet market	70.9	2.1	15.3	0.0	11.7	0.0
Total	56.3	4.2	17.5	0.2	20.6	1.2

For example, if a test failed because of nitrofurans, then from Assumption 1, the probability range is [62.3%, 97.5%] that farming was the risk source and [2.5%, 37.7%] that circulation was the risk source. Aggregating these ranges across all failed tests, Table 5 presents the ranges of the overall risk from each risk source for tests conducted at each SC location.

5. Insights

The first main insight of the analysis in Section 4 is that farming and manufacturing are the major sources of risk for aquatic products (see Table 5). A natural question is to what extent the current policy of the CFDA addresses these sources of risk and allows traceability to them.

The second main insight is that WSMs and wet markets are undersampled, allowing many high-risk aquatic products originating from farms to arrive to consumers unsupervised. Figure 5 and the SC flow analysis in Section 3.1 highlight the fact that the vast majority of aquatic product supply from farms passes through WSMs and wet markets before being sold to restaurants and individuals. WSMs and wet markets also seem to carry the riskiest products from farms, as they have the highest failure rates of any SC locations, and most of this risk is attributable to farming. In contrast, very little of the risky supply originating from farms passes through manufacturers or retail/supermarkets. Table 5 shows that manufacturers source safe products from farms, and the analysis in Section 3.2 provides evidence that retail/supermarkets source safer products from WSMs than restaurants do. Despite this, Figure 5 shows that the CFDA allocates just 21% of aquatic products tests to WSMs and wet markets.

Additionally, WSMs are large consolidation points, distributing 70%-80% of the supply for aquatic products (see Section 3.1). Therefore, WSMs offer logistical advantages for the broad sampling of products from risky farms. Many samples could be collected at a single location, with a possible cost reduction.[10] Also, WSMs typically provide the highest degree of traceability to the farms (Ma 2015). Although traceability systems still need to improve, WSMs offer the potential for traceability to specific high-risk farms because of their location in the SC.

Although more research is clearly needed to better understand important aspects related to developing an optimal regulatory strategy, there are many reasons to believe that the current policy could ultimately be improved by adapting more *risk-based sampling* and in particular, by increasing focus on WSMs and wet markets. That said, the design of specific policies will have to consider and analyze various endogeneity issues that could create incentive problems if tests are reallocated (i.e., fewer tests at retail/supermarkets could result in more risk at those locations). Potentially, the CFDA could simply conduct more tests, with additional tests aimed at WSMs and wet markets, thereby creating stronger incentives at those risky SC locations while not reducing incentives elsewhere.

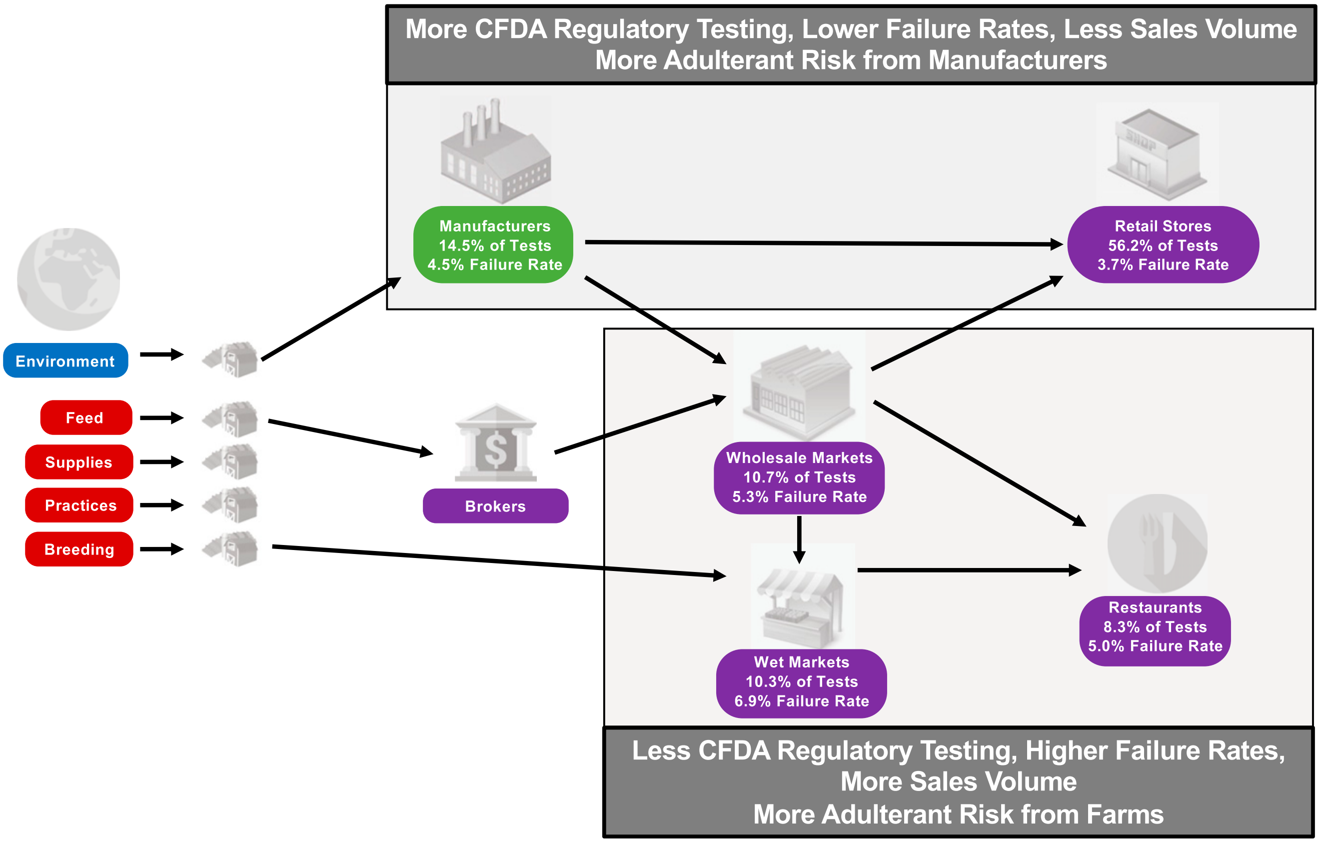
The third main insight is that *risk-based sampling of individual companies* and better testing coordination could mitigate risk originating from manufacturing. Table 5 shows that risk associated with manufacturing is most prevalent on-site (at manufacturers), at retail/supermarkets, and at restaurants. Risk originating from manufacturing is also more traceable to the source, as it relates to packaged products that identify the specific manufacturer. Using the same type of SC source analysis described in Section 4, manufacturers can be "flagged" as *high risk* in scenarios where they were likely to have introduced the detected adulterants responsible for failed tests. The idea is that such a flag should trigger another test on the manufacturer's premises to address potential problems at the source, as presented in Figure 6.

To increase statistical power when evaluating this approach, the adulterant dictionary was expanded to cover all products (see Online Appendix EC.5). Specifically, each adulterant in the CFDA database is associated with either "manufacturing" or "nonmanufacturing." All failed tests of manufactured products in downstream SC locations are then considered as shown in Figure 6, with the respective manufacturers flagged as high risk when the failure was because of an adulterant associated with manufacturing."

Table 5. Risk Source Analysis: Percentage of Adulteration by Risk Source for Each SC Location

Sampled location SC type	Percentage of adulteration by risk source [min, max]			
	Environment	Farming	Manufacturing	Circulation
Manufacturer	[0.7,37.4]	[4.8,6.7]	[55.8,92.5]	[0.1,2.1]
Restaurant	[0.5,3.6]	[39.0,55.1]	[40.1,43.2]	[1.2,17.3]
Retail/supermarket	[6.1,15.7]	[40.3,53.2]	[30.1,39.8]	[0.9,13.9]
Wet market	[7.6,14.9]	[52.9,69.7]	[14.2,21.5]	[1.2,18.0]
Wholesale market	[13.9,18.0]	[43.8,59.3]	[21.7,25.7]	[1.1,16.6]
Total	[6.6,16.1]	[40.8,54.6]	[28.3,37.8]	[1.0,14.7]

Figure 5. (Color online) Overview of Risk Sources, Current CFDA Testing Allocations and Outcomes, and Product Flow in the Aquatic Supply Chain



Based on this methodology, there were 4,946 manufacturers in the CFDA data set flagged as high risk. Only about 20% of these high-risk manufacturers were tested on-site during the six months after the flag, yielding a failure rate of 10.0% for targeted testing, compared with an overall on-site manufacturer failure rate of 4.2%. An exact binomial test shows that this approach identifies riskier manufacturers, with a significance level of $p < 1 \times 10^{-6}$. Full calculations are included in Online Appendix EC.6. An operational tool, shown in Figure 7, is used to communicate the results of this analysis.

Although this risk-based sampling of individual companies is very intuitive, it has been enabled in two ways by the work in this paper.

i. *Data integration.* In total, 30.6% of the high-risk manufacturer flags were created from tests outside of the manufacturer's province. Because of the dispersed

Figure 6. (Color online) Targeted Testing of Manufacturers

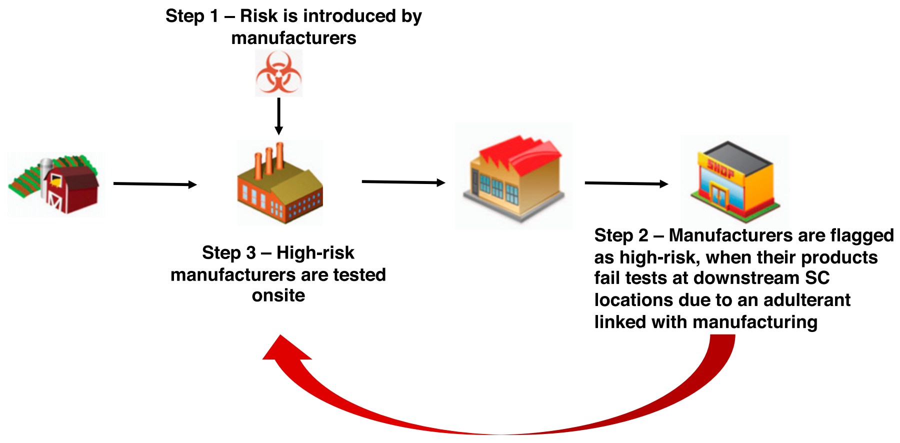
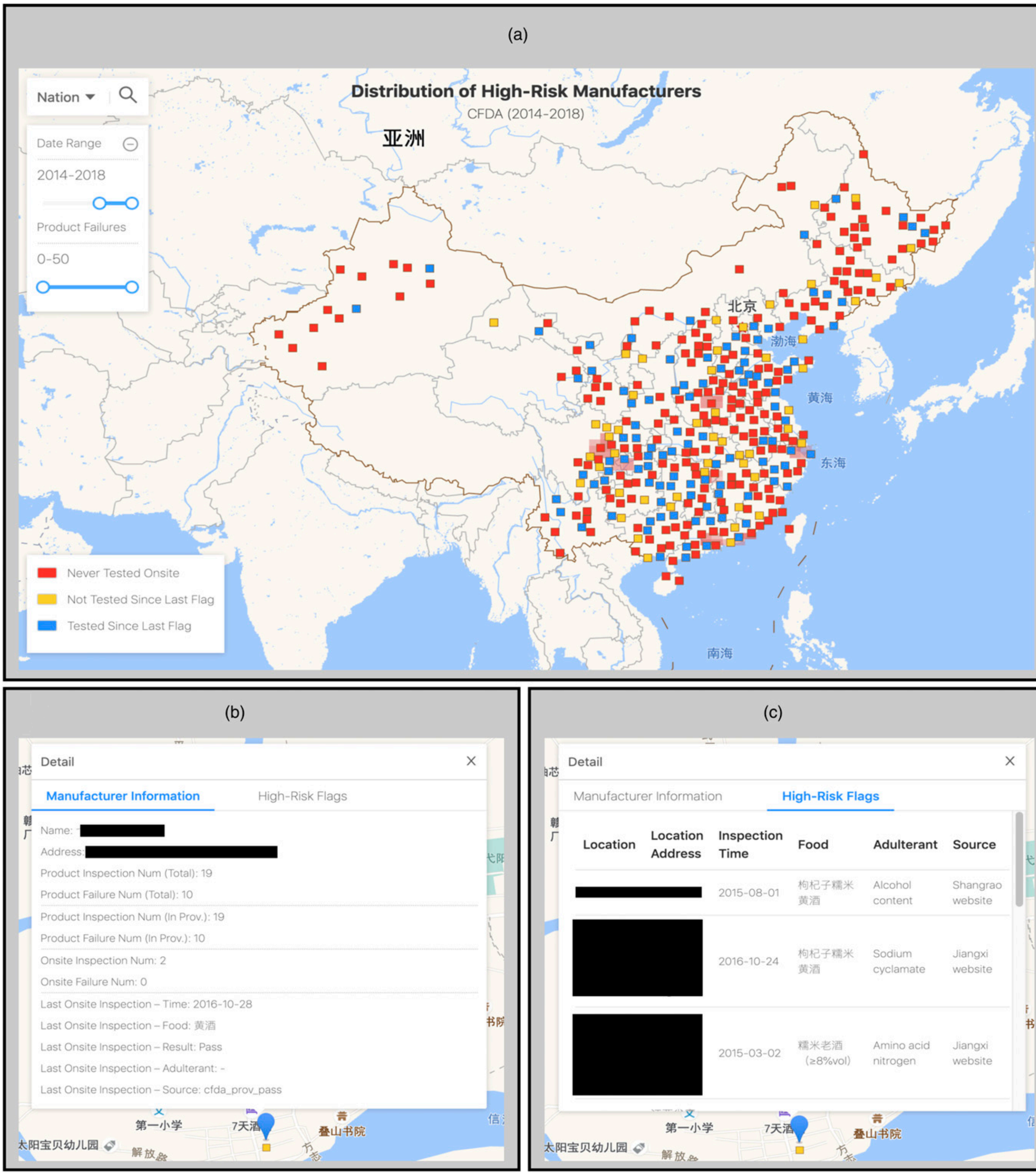


Figure 7. (Color online) Operational Tool, Created in Collaboration with iSoftStone

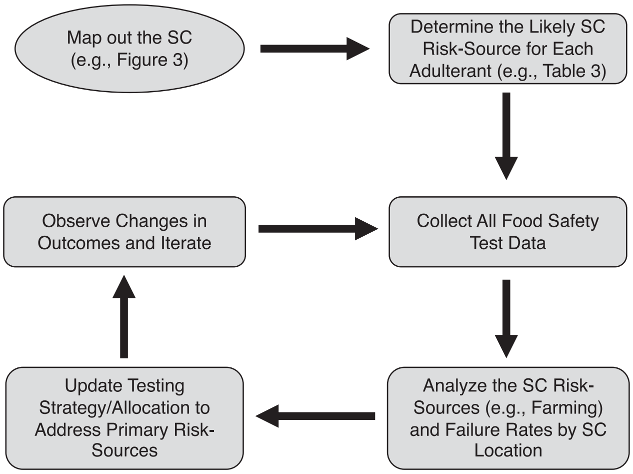


Notes. (a) User interface for the web-based tool, with squares denoting high-risk manufacturers. (b) Manufacturer information (redacted) for each high-risk manufacturer. (c) Information describing why the high-risk flags were created (see Figure 6).

regulatory structure and potential lack of data sharing across CFDA organizations, they are not likely to be able to integrate this breadth of data at the moment. This illustrates the enormous benefit that could result from data sharing.

ii. *Risk source analysis*. To assess value of the adulterant risk source analysis (step 2 in Figure 6), as opposed to on-site testing of all manufacturers with products failing in downstream SC locations, the analysis was repeated for adulterants attributed to

Figure 8. Heuristic Framework for Risk Source Analysis of Food SCs



"nonmanufacturing." The on-site testing of these manufacturers has a failure rate of 3.7%, which is less than the overall manufacturer failure rate of 4.2%. More details, including statistical tests, are in Online Appendix EC.6.

Because reallocating tests from other manufacturers to these high-risk manufacturers also does not add to the direct operations costs for the CFDA, there seems to be a significant net benefit to adopting such an approach.

6. Concluding Comments

This paper highlights how SC analytics can provide several important strategic and operational insights regarding the allocation of testing resources in the freshwater aquatic SC in China. This is enabled by the construction of a comprehensive data set of over 2.6 million food safety test results conducted by the CFDA throughout China between 2014 and 2018, currently posted in nonstandardized formats across 247 websites and over 60,000 files.

The common theme is that risk-based sampling strategies that seek to test at the SC risk sources could potentially be more effective than the current CFDA testing strategy. Specifically, the paper presents an aggregated risk source analysis of aquatic products to show that the main risk sources are farming and manufacturing. The paper then considers SC supply flow to provide evidence that the current CFDA approach of testing heavily at retail/supermarkets is limited in its ability to monitor risk originating from farms, whereas allocating more tests to WSMs and wet markets has the potential to significantly improve that. In addition, the paper illustrates how risk source analytics leveraging the integrated data can identify high-risk manufacturers that should be prioritized for testing.

Although this paper focuses on the freshwater aquatic SC in China, the framework could be used to generate insights for other food SCs and countries as well. A flow diagram for how this might be implemented is given in Figure 8.

The paper raises many important questions for further research. For example, it would be interesting to study to what extent testing food in different SC locations differs in terms of the ability to identify problems, incentivize safer behavior by food producers and manufacturers, create transparency as to where the risks are being introduced, and affect the cost of testing. Such analysis would inform more refined optimization of the related resource allocation. Another interesting set of questions relates to studying and modeling of the adulteration mechanisms and their incentives, which can in turn lead to identification of additional measurable risk drivers that can be incorporated into risk analytics models and further inform risk-based regulatory strategies.

Recently, the concept of risk-based standards for managing food SCs has been recognized and promoted by the U.S. FDA as a priority for global adoption (U.S. Food and Drug Administration 2019). Thus, the paper strives to serve as a first step toward developing a new and needed body of work on risk-based analytics-enabled regulatory strategies to address the global risks of food safety and food adulteration.

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Endnotes

[1] See "China reveals 300,000 children were made ill by tainted milk" (https://www.telegraph.co.uk/news/worldnews/asia/china/3540917/China-reveals-300000-children-were-made-ill-by-tainted-milk.html).

[2] The CFDA is split into separate organizations, including a state-level CFDA, 31 provincial CFDAs, and 334 prefecture-level city CFDAs. For remaining prefectures, some do not seem to post test results, some have inaccessible websites, and others have website structures that make automated data collection more difficult.

[3] See Order No. 11 of the State Food and Drug Administration (http://www.gov.cn/gongbao/content/2015/content_2827226.htm).

[4] The Chinese government published *Program for Deepening the Reform of Party and Government Organization* in March 2018: three state-level organizations (the CFDA, the State Administration for Industry and

Commerce, and the State Administration for Quality Supervision and Inspection and Quarantine) merged into one organization named the State Administration for Market Regulation, although this will not affect testing responsibilities.

[5] See Statistical Yearbook of China Commodity Exchange Market, 2018.

[6] Based on interviews with an official from the Zhejiang CFDA, and surveys at aquatic WSMs in Zhejiang (Jin et al. 2019).

[7] See People's Republic of China Food Safety Law, 2015 (http://www.gov.cn/xinwen/2015-04/25/content_2852919.htm). The web page has also been archived at (https://archive.is/JUvkY).

[8] Pathogens are excluded because it is not obvious how to determine the likely SC source, and they can penetrate the SC in any of its stages. Labeling violations are excluded because they are not related to adulteration but rather to food fraud (i.e., the misrepresentation of food being sold), and like pathogens, they can also be introduced in multiple SC locations.

[9] Although the vast majority of interviewees thought farms introduce more risk than circulation, it should be noted that this was not unanimous.

[10] On the other hand, the supply moves rapidly in and out the WSMs, often overnight, which might require slightly higher wages for collection officers.

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