Public health risks arising from food supply chains: Challenges and opportunities

Public Health Risks Arising from Food Supply Chains: Challenges and Opportunities

Lu Chen[1], Donovan Guttieres[1], Retsef Levi[2], Elisabeth Paulson[3], Georgia Perakis *[2], Nicholas Renegar[3] and Stacy Springs[1]

[1]Massachusetts Institute of Technology, Center for Biomedical Innovation

[2]Massachusetts Institute of Technology, Sloan School of Management

[3]Massachusetts Institute of Technology, Operations Research Center

August 13, 2021

Abstract

Safe, healthy, and resilient food supply chains are essential to ensuring the livelihood and well-being of humans and societies, as well as local and global economies. However, the ability to provide and sustain access to nutritious and safe food continues to be a major concern and a challenge for almost any country around the world, including developed countries. Some serious and global public health risks arise from food supply chains. These include food safety and adulteration risks in which unsafe food is sold for human consumption, antimicrobial resistance risks that are becoming increasingly prevalent due to the overuse of antibiotics, zoonotic disease risks (i.e., viruses and diseases that transfer from animals to humans through food supply chains), food waste, and also food security issues such as food deserts and the diet disparity among different segments of the population. This article gives an introduction to these various risks and reviews directions in the current academic literature to address these challenges. The article also seeks to highlight important new research directions in these areas, and especially those that might be of significant interest to the operations research community.

Keywords— Food safety; Food security; Zoonotic Disease; Supply Chain; Food Waste;

1 Introduction

Safe, healthy, and resilient food supply chains are essential to ensuring the livelihood and well-being of all. However, the ability to provide and sustain access to nutritious and safe food continues to be

*Corresponding author: Georgia Perakis, georgiap@mit.edu

a major challenge for most countries. Inherent features of food supply chains give rise to significant social, economic, environmental, and public health vulnerabilities. In many developing countries, for example, agriculture supply chains are highly fragmented and opaque, consisting of millions of smallholder producers, often family-owned and/or underdeveloped farms, as well as a complex network of brokers and intermediaries. These structures create a myriad of issues ranging from food waste, to price irregularities, poverty, nutritional deficiencies, and foodborne illness.

The scale of these challenges is greatly enhanced by the growing demand for food, especially for protein, as a result of increasing average individual incomes and global population growth [Godfray et al., 2018]. Additionally, food supply chains are becoming more global and complex, with insufficient quality surveillance, as consumers demand a wider variety of products. In 2019, close to 15% of the food supply in the U.S. was imported from more than 200 countries or territories, including 32% of fresh vegetables, 55% of fresh fruit, and at least 94% of the seafood that Americans eat each year [U.S. Food and Drug Administration, 2019].

In many developing countries, agriculture continues to be a prominent employment sector and a significant contributor to the economy. Inefficiencies across the food supply chain can lead to subsistence-oriented farming, low yields, limited market access, and insufficient profits for smallholder farmers that lead to poverty [Meemken and Bellemare, 2019]. Therefore, farmer welfare continues to be a social, economic, and political priority. Structural opaqueness in food systems can lead to various types of food safety risks: economically motivated adulteration (EMA) such as the extensive use of illegal antibiotics and drugs and fraud, insufficient supply chain practices that lead to environmental and water contamination (e.g., heavy metals) resulting in food waste, and foodborne illness as a result of consuming unintentionally contaminated food, among others. In 2010, contaminated food led to approximately 600 million cases of foodborne diseases and 420,000 deaths [Havelaar et al., 2015]. Substandard food products lead to large economic loss, close to $110 billion each year in low- and- middle-income countries as a result of lost productivity and medical expenses, without accounting for hard-to-measure costs of domestic food market disruptions and consumer product avoidance [Jaffee et al., 2019].

Zoonotic diseases, viruses that transfer from animals to humans through food supply chains, such as avian flu and COVID-19, also contribute to significant public health risks [Abebe et al., 2020]. The risk of new and re-emerging pandemics has led to calls for changing food supply chains of live animals [Webster, 2004]. Moreover, antimicrobial drugs used in animal farming contribute to the development of antimicrobial resistance that can spread to human pathogens and affect large populations [Ruiz and Alvarez-Ordonez, 2017].

The urgent need to address inefficiencies in food supply chains is also seen by the growing number of people worldwide affected by hunger since 2014, with nearly two billion people in the world exposed to some level of food insecurity in 2019 [FAO and IFAD and UNICEF and WFP and WHO, 2020]. Healthy diets are not accessible or affordable in all geographies, leading to growing diet-related health costs. The relatively high prices of healthy and fresh food, compared to the increasingly large volumes of high-calorie, low-cost alternatives has led to a *diet disparity*—a phenomenon where low-income individuals tend to consume less healthy diets on average. One and a half billion people across the globe cannot afford a nutritionally sound diet [FAO, IFAD, UNICEF, WFP and WHO, 2020]. Even in developed countries, access to healthy and fresh food, as well as the cost of these foods, pose barriers to low-income households who tend to have poor diet quality, leading to increased rates of certain poor health outcomes. Therefore, ensuring that *all* individuals can benefit from increased globalization should be a key priority. In the U.S., many government interventions exist to increase access to, and affordability of, fresh and healthy foods. However, many of these interventions have not resulted in their desired efficacy.

Although hunger is on the rise and billions of individuals across the globe are food insecure, about one-third of all food produced is wasted FAO [2014]. Food waste occurs at every level of the food supply chain for a wide variety of reasons. Furthermore, the extent of food waste can vary significantly depending on the location and type of food, with the highest levels of waste occurring for fruits and vegetables. Developing effective strategies for decreasing waste along the supply chain is critical to increasing the availability of healthy, affordable food for people in need.

Although not the focus of this paper, global food supply chains interact with the environment in many ways. Current agricultural practices, often optimized for productivity, have a detrimental impact on the environment, including excessive water consumption, greenhouse gas emissions (with livestock accounting for close to 15% of global GHGs), land degradation, biodiversity loss, and use of pesticides, among other [Gerber et al., 2013].

1.1 Our Contribution

Transformations in food supply chains, in particular through the use of advanced analytics and related technologies, are needed to better monitor different types of risks and guide interventions. This article reviews the current literature, presents examples of existing research, discusses challenges in managing various types of risks, and highlights potential opportunities for future research to make the food supply more resilient and sustainable. In particular, the paper focuses on five challenges/areas of research:

1. Food Safety and Adulteration Risks
2. Antimicrobial Resistance Risks
3. Zoonotic Disease Risks

4. Food Waste in Supply Chains

5. Food Security, Food Deserts, and the Diet Disparity

Often, lack of regulatory resources or inefficiency in allocating limited resources leads to reactive rather than proactive risk management. Another challenge is that available data is often inadequate to build robust analytical tools. Relevant data across the food supply chain resides in multiple sources (some are publicly available and others privately owned) and is often unstructured, incomplete, and non-standardized. There is also limited experimental data available in the agricultural sector, especially across the supply chain, making it difficult to infer or predict the impact of interventions. Creating optimal conditions for data sharing, for example through a data marketplace with appropriate economic incentives, is needed to increase the volume, quality, and type of data available to enable more robust data-driven analytics. Automating the integration of data in different formats is a long-term fundamental challenge. Companies spent an estimated $3.8 billion on data integration in 2012, with an average annual growth rate of 8.7% [Bernstein and Haas, 2008]. Approaches using deep learning models, mixed integer programming, autoencoders to couple different data modalities in the latent space, among others, are allowing for more elaborate tools for AI-assisted data integration.

Data-driven, machine learning-based approaches offer new opportunities to diagnose and monitor risks to provide decision support at different scales of food supply chains. These can range from developing better cropping strategies in the face of variable field environments to more proactive policies for enhanced productivity and food safety in the U.S. and worldwide. The availability of data-driven approaches and cheaper, faster, and more robust sensing technologies highlight the potential of novel approaches in solving complex systemic challenges with limited resources. Supply chain analytics can serve a critical complementary role in: (i) creating new useable datasets; (ii) developing predictive risk models; and (iii) informing risk-based regulatory policy and resource allocation. Moving towards more digital, risk-based management of food supply chains is in line with The Food Safety Modernization Act (FSMA) passed by the U.S. government in 2011 to enable predictive capabilities to drive preventive actions. The U.S. FDA's blueprint for a New Era of Smarter Food Safety released in 2020 further emphasizes the need to enhance traceability of food back to its source and improve predictive analytics across the entire supply chain to respond more rapidly to public health risks arising from inadequate food supply chains [U.S. Food and Drug Administration, 2020].

The remainder of the paper is organized according to the five research topics listed above. Within each topic, the paper presents background information, an overview of current practices, and operations research (OR)-related opportunities for future research.

2 Managing Food Safety and Adulteration Risks

Awareness of food safety and adulteration risks have increased significantly in recent decades, as a result of various public scandals. One prominent example was the 2008 melamine incident in China, in which baby formula was contaminated with melamine through the dairy supply chain, causing multiple deaths and more than 50,000 babies to be hospitalized with serious injuries[1]. A more recent example is the repeated outbreaks of foodborne illness occurring at Chipotle restaurants in the U.S., which have resulted in more than 1,100 illnesses and led the U.S. Food and Drug Administration (FDA) to fine the restaurant chain $25 million[2].

One approach to classifying food adulteration incidents is through the perspective of the underlying intentions that drove the incident. On one end of the spectrum is adulteration due to *unintentional negligence*, in which food safety issues arise due to a lack of expertise, poor sanitary conditions, environmental pollution, or some other unintentional failings within the food production supply chain. The foodborne illness outbreaks at Chipotle are an example of adulteration due to unintentional negligence. On the other side of the spectrum there is intentional adulteration due to *terror motives*, in which biological/chemical agents are intentionally added to the food supply chain for the purpose of causing terror or damage. In between these two is *economically motivated adulteration* (EMA) in which adulterants are intentionally added during food production or manufacturing in order to improve either the yield or perceived quality, and in turn to increase profit. The melamine incident in China, in which melamine was intentionally added to the dairy supply chain to increase protein content, is an example of EMA.

Of these three types of risk scenarios, managing terror risks is somewhat unique, and has typically focused on preventive measures within key strategic areas of food supply chains. For example, when terrorism fears were heightened following the 2001 world trade center attacks, researchers explored strategies to prevent releases of dangerous chemicals (e.g., botulinum toxin), in cold drink supply chains such as milk [Wein and Liu, 2005]. In contrast to terror risks, governments often manage both unintentional negligence and EMA risks under the same programs and often run by the same regulatory bodies. The rest of this section describes government policies to manage these other two types of risks, as well as challenges, current research, and opportunities.

[1] (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] (Chipotle Mexican Grill Agrees to Pay $25 Million Fine to Resolve Charges Stemming from More Than 1,100 Cases of Foodborne Illness). *https://www.fda.gov/inspections-compliance-enforcement-and-criminal-investigations/press-releases/chipotle-mexican-grill-agrees-pay-25-million-fine-resolve-charges-stemming-more-1100-cases-foodborne*

2.1 Current Government Policy to Manage Food Safety

To manage food safety risks around the world, governments typically follow somewhat similar procedures. First, governments set laws to regulate standards for food production and the content of final food products. Specifically, the government decides which additives, pesticides, and other adulterants are completely outlawed in food production, and which ones are allowed but only within a specific concentration. In the U.S., for example, these standards were set through laws including The Pure Food and Drug Act of 1906, the Food Additives Amendment of 1958, and the Food Safety Modernization Act of 2011 [FDA, 2018]. Government regulatory organizations are then responsible for ensuring that these laws and standards are actually followed. Failure to abide by food safety regulation and laws typically result in fines or sanctions that inhibit a company's ability to do business [U.S. FDA, 2018]. In more extreme cases these can lead to criminal charges, even including capital punishment in cases such as China's melamine incident[3]. Inspection/testing of food consignees (importers), imported shipments, producers (farmers), overseas and domestic manufacturers, and final food products is used to ensure that laws and safety standards are followed. However, there are several challenges in creating good inspection/testing allocation strategies that are common among governments worldwide:

1. **Scale and Heterogeneity -** Unlike regulating pharmaceuticals, where large pharmaceutical companies manufacture enormous batches of a homogeneous product that must adhere to a pre-specified 'formula', the scale of heterogeneous food that must be managed is truly vast. Not only are there many millions of farmers and food manufacturers (compared to relatively few pharmaceutical companies), but there can also be more heterogeneity in the 'formula' and safety of products from the same 'batch'.

2. **Traceability/Opaqueness Issues -** Food supply chains also suffer from a lack of traceability, defined as the ability to conduct full backward and forward tracking of the product to determine the specific locations and life history in the supply chain, all the way back to the farm level, by means of records [Opara, 2003]. This is true of all countries, and especially relevant for food supply chains with a large number of smaller farms. A higher level of traceability improves food safety, by enabling issues to be quickly traced to the source [Jin et al., 2021]. Traceability also creates a higher level of accountability in the case of EMA. These issues with traceability have engendered research efforts in the agricultural economics community to create better traceability systems, understand their impact on food safety, and incentivize more traceability adoption [e.g. Hobbs, 2004, Hobbs et al., 2005, Pouliot and Sumner, 2008, Starbird and Amanor-Boadu, 2006].

[3](China executes two for tainted milk scandal). *https://www.theguardian.com/world/2009/nov/24/china-executes-milk-scandal-pair*

3. **Lack of Regulatory Resources -** As a result of the complexity of food supply chains, governments lack the regulatory resources to inspect/test as frequently as they may want. For example, the U.S. FDA currently oversees more than 40 million imported food product lines (shipments) per year and has to decide whether each is safe to let into the U.S. However, the FDA only has the regulatory resources to inspect 1-2% of these shipments [Racino, 2011]. As another example, China has 200 million mainly small and family-owned farms, but has the regulatory resources to sample only a few million food products per year [Lowder et al., 2016].

4. **Lack of Usable Data -** Historically, governments have lacked high quality data based on which it is possible to develop risk-based inspection/testing allocation policies. However, this is changing quickly. For example, China's Food Safety Law of 2015 mandated that the central, provincial, and prefecture level China Administration for Market Regulation (AMR) organizations begin publicly posting all food safety test records online in order to facilitate research [HFG, 2016]. Similarly, the European Commission has created the *The Rapid Alert System for Food and Feed*, so that EU member countries can engage in real-time data sharing about emerging food safety threats [European Commission, 2019]. However, even with this improved public availability of data, there are still serious challenges of data integration, which will be a central theme of this thesis.

Although governments have historically used largely random inspection/testing allocation policies—as they lacked the data to implement more sophisticated methods—there has been a global push for more advanced risk-based management systems. In recent years, the U.S. FDA has begun exploring the applications of predictive analytics in helping to target potentially contaminated foods[U.S. FDA, 2019]. Moreover, the FDA has begun "new approaches to food safety, leveraging technology and other tools to create a safer and more digital, traceable food system" under their program titled the 'New Era of Smarter Food Safety' [U.S. FDA, 2021]. At the same time, the China State Council is also developing risk-based food safety inspection policies that allocate more resources to high-risk product categories and companies [Xinhua News Agency, 2019].

2.2 Research Directions and Opportunities

There have been significant research efforts in academia and government in recent years to leverage data in order to better understand the risk-based management of food supply chains. One of the first such efforts was the FDA's Predictive Risk-Based Evaluation for Dynamic Import Compliance Targeting (PREDICT) model, which has been in operation since 2011 [GAO, 2016]. PREDICT is a machine learning tool to provide recommendations for shipment sampling of imported food (where a shipment is held at a U.S. port to ensure it meets food safety standards) based on data such as recalls, news stories, and the regulatory history of the relevant companies. More recent examples include using publicly available databases of food safety complaints to identify emerging food safety risks (e.g. the use of text mining and machine learning algorithms by Kate et al. [2014] in Singapore and content analysis of public databases by Liu et al. [2015] in China), statistical analysis of risks across different product categories [Liu et al., 2017], and using data related to the region, farming system, irrigation source and sampling time as food safety risk factors [Pagadala et al., 2015]. The latter strategy exemplifies the need for database integration, as many discrete data sources had to be combined to understand the statistical effect of risk drivers at an aggregate level.

Another popular stream of research focuses on early warning systems, where the goal is to evaluate the risk state of an overall food system to preemptively identify food safety issues. Some researchers have shown that the broader food system environment can predict the emergence of food safety issues through statistical analysis [e.g. Kleter and Marvin, 2009]. In recent years, this has led to papers on early warning signal systems using machine learning. For example, Marvin et al. [2016] use Bayesian Networks to predict fraud in seafood, meat, fruits, and vegetables based on multiple drivers of risk. Similarly, Verhaelen et al. [2018] use autoregressive models to predict food safety and food fraud based on leading indicators of prices and commodity flows, and Zhang [2020] uses support vector machines for early warnings in food safety systems.

Many of the above research streams leverage data to create statistical and machine learning models that predict food safety risks. However, one direction which has not been as widely explored in the literature, and which might be of particular interest to the operations research (OR) community, is to understand how supply chain structure can be used to predict risk. As a reference point, Figure 1 below gives an overview of a supply chain for an international food shipment. Specifically, a shipment originates at a *manufacturer* that packages the product. From here, the shipment is moved to a *place of receipt* where it is collected by a *shipper*. Note that in the case of vertical integration, the shipper and manufacturer might be the same entity. The shipper transports the shipment from the place of receipt to a *foreign port*, where it is loaded onto a ship destined for the U.S. The shipment enters the U.S. through a *U.S. port*, and from there it is delivered to the *consignee*.

Evidence from various analyses of food adulteration incidents suggests that supply chain complexity, opaqueness, and traceability play a major role in incentivizing and enabling these incidents. For example, Huang et al. [2018] and Babich and Tang [2012] provide empirical and modeling frameworks to characterize the supply chain dynamics and operational characteristics of firms engaged in food adulteration. In particular, Huang et al. [2018] provides evidence through Heckman's sample

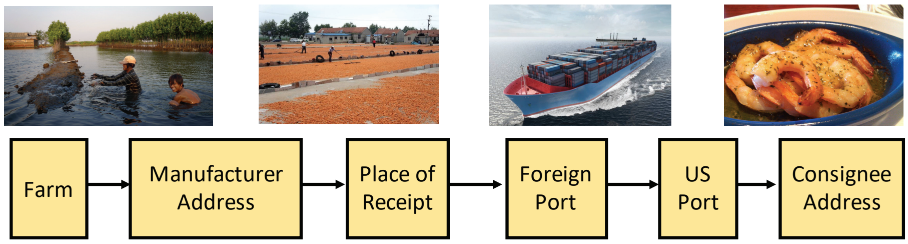


Figure 1: International Food Supply Chain

selection model that more distributed farming supply chains, featuring a large number of entities each responsible for a small fraction of the overall output, tend to have more problems with EMA. In Levi et al. [2020] it is shown how predictive models using measures of supply chain complexity and other features describing international shipping networks can be used to identify firms importing unsafe food into the U.S. This is done by integrating private FDA shipment and regulatory databases, a public bill of lading shipment database, and publicly available (online) information about the firms.

Another avenue of research well suited for the OR community is to study how inspections/tests should be allocated across different stages of the supply chain. Strategically allocating *where* tests are conducted along the supply chain might have a different ability to identify risky products than the current approaches which often focus on testing closest to the consumer, as well as a different outcome in incentivizing safer food production. For example, in Jin et al. [2021] food safety test allocations are reviewed for China's aquatic products supply chain, by leveraging a unique, self-constructed data set of 2.6 million food safety tests collected from 60,000 files, with over 15,000 unique data schemas, and posted across 247 China Food and Drug Administration (CFDA) websites. A supply chain risk driver analysis is used to show that China's current test allocations sample infrequently at wholesale and wet markets despite being supply chain consolidation points through which the riskiest supply from farms tends to flow. There are many open research problems in this area, including studying how tests should be allocated at various supply chain points and how to incentivize safety through the formulation of optimization frameworks. One of the first examples of this work is in Wang et al. [2020], where testing for aflatoxins and dioxins was evaluated across the Dutch dairy supply chain.

3 Managing Antimicrobial Resistance Risks

Antimicrobial resistance (AMR) is a growing global threat to public health that is associated with the overuse and misuse of antimicrobial drugs in farming and clinical settings. In the U.S. alone, there are over 2.8 million AMR infections and over 35,000 deaths resulted from AMR annually as estimated by the Center for Disease Control (CDC) [CDC, 2019]. The high volume of antimicrobial drugs used in animal farming promotes the development of antimicrobial-resistant bacteria that can spread along food chains through direct human-animal interaction or indirectly through the environment [Ruiz and Alvarez-Ordonez, 2017]. Some AMR genes can horizontally transfer from non-pathogenic bacteria to pathogenic bacteria in humans, resulting in the development of multidrug-resistant superbugs that seriously threaten public health [McInnes et al., 2020]. The recent identification of bacteria and relevant gene element (MCR-1) responsible for resistance to colistin, a crucial last resort antibiotic option, highlights the importance to take immediate actions to monitor and mitigate AMR risks in food chains [Liu et al., 2016].

Food supply chain features can drive the development of AMR. For example, the small household-based contract farming that is common in developing countries tends to shift economic risks to farmers and, as a result, incentivizes the high use of antibiotics by farmers to protect the low-profit margin [Hinchliffe et al., 2018]. The fragmented, complex, and opaque food supply chain in developing countries also makes it challenging to implement regulations and leads to weak supervision and inconsistent farming practices. AMR risks driven by these supply chain features not only impact developing countries but can cross borders and harm global health [Nadimpalli et al., 2018]. A global surveillance system is essential to monitor and predict AMR trends and guide regulatory efforts.

3.1 Research Directions and Opportunities

Currently, there lacks a systemic surveillance system that monitors global AMR trends, particularly in food animals. While some developed countries like the U.S. have established surveillance systems that monitor enteric AMR bacteria in animals, animal products, and humans using traditional antimicrobial susceptibility testing (AST) and whole-genome sequencing (WGS) [FDA, 2020], AMR trends in developing countries are poorly documented and most data are available as AST data in point prevalence surveys for specific regions. Integrated AST data across regions could be useful to assess global AMR trends, but there are some significant challenges to meaningful analysis, which involve synthesizing AST data with multiple pathogens and compounds, variable protocols, sample sizes, and breakpoints across different regions. One study has integrated over 900 published AST datasets in low- and middle-income countries and used geospatial models and composite metrics of resistance to map global AMR trends and identify hotspots, which provides a baseline for monitoring AMR in food animals and informs targeted intervention in most affected regions [Van Boeckel et al., 2019].

Besides traditional AST testing, WGS has been used to rapidly detect AMR based on bacteria's genome sequence. WGS generates large datasets and requires advanced bioinformatics tools and machine learning to analyze the genomic structure of the microbial resistome, track AMR evolution and spread, and inform regulatory decisions [Holden et al., 2013, Baym et al., 2016]. Standardization of reference databases, integrated analysis of AST and WGS data, and phenotypic predictions based on genome data are some future directions to improve AMR surveillance and enhance global health.

In low- and middle-income countries, the monitoring and research of AMR in food supply chains is greatly restricted by logistic challenges due to the complex and dispersed local food supply chains. Countries like China have set up regular AMR surveillance programs, however, the current approach focuses on farms, which is resource-intensive and can only cover a very small fraction of farms infrequently [MoA, 2019]. Previous work has identified wholesale markets as a consolidation point in food supply chains in China and has shown that a risk-based sampling inspection approach at wholesale markets can identify more problems than the traditional approach [Jin et al., 2019]. As wholesale markets consolidate supplies of live animals or animal products from nearby farms, monitoring AMR in wholesale markets should be able to reflect regional AMR trends. Since antibiotic residues are a major cause of failure in food safety testing, it is likely that food safety risks in markets will be informative of the market's AMR risks and can be leveraged to guide the development of a risk-based sampling strategy. Instead of focusing on farms, testing at wholesale markets in a risk-based way could allow regulators to monitor larger areas from one point with optimal resource allocation, and inform further targeted testing of farms to identify the origin of AMR risks.

Another gap in managing AMR is regarding the transmission of AMR bacteria and transfer of antimicrobial-resistant genes (ARG) in the food supply chain, it is not clear how and where are AMR bacteria transmitted to humans [He et al., 2020]. Studies have identified multiple pathways for ARG to transfer to human pathogens, both directly through handling animals or animal products, and indirectly through contacting the environment contaminated with ARG [Founou et al., 2016, Chique et al., 2019]. It is noteworthy that isolates from clinical samples sometimes do not match AMR and antibiotic residue in clinically relevant environmental samples, which underscores the need to better understand the AMR exposure mechanisms in humans [Grosso-Becerra et al., 2014]. Supply chain analytics provides important insights on key interfaces and can help predict high-risk areas of exposure, coupling with genomic data that could track the spread of AMR in food supply chains, can support the development of quantitative exposure risk models, and enable the evaluation of potential interventions to mitigate exposure risks.

4 Managing Zoonotic Disease Risks

Risks from zoonotic diseases, which are those that transmit from animals to humans, have also reached the public consciousness following several pandemics such as SARS in 2002, swine flu in 2009, and more recently COVID-19. As a consequence of these pandemics, in particular COVID-19, there has been widespread research within the OR community related to pandemic management response including interventions to stop disease spread and medical planning to account for capacity issues, using techniques such as SIR models and gradient-boosting prediction algorithms [e.g., Li et al., 2020, Sun et al., 2020]. However, little research has been done within the operations community on how these diseases spread to humans from food supply chains or how to prevent the patient zero infection. The rest of the section will discuss research opportunities in these areas.

A review of zoonotic disease outbreaks in the 21st century confirms that many of them have spread to humans from food supply chains and in particular from live animal markets. Notably, many of the zoonotic disease outbreaks in China, including SARS and avian influenza, have been associated with large wholesale markets (WSMs) and smaller wet markets (WMs), both of which play a unique and prominent role in China's food supply chains [Jin et al., 2021, Editors, 2020]. While there is still debate over COVID-19's origins, one hypothesis ties the first known cluster of COVID-19 to the Wuhan Huanan Seafood Market, and a more recent COVID-19 outbreak spread from Beijing Xinfadi Seafood Market[4] [5]. Likewise, the 2003 SARS outbreak was associated with markets in Foshan, brucellosis cases in 2005-2010 were linked to pork markets in Guangdong, and avian influenza H7N9 cases from 2013-2017 were associated with poultry markets in Shanghai and Anhui [Guan et al., 2003, Lee et al., 2013, Woo et al., 2006].

4.1 Research Directions and Opportunities

As a result of this pattern, both within and outside of China, there have been calls for a fundamental redesign of WSM/WM management and perhaps even their closure [Neuman, 2020, e.g.,]. However, these markets are major distribution points in the Chinese agricultural supply chain, that consolidate 70-80% of the supply for many product categories [Jin et al., 2021]. Closing these markets would affect the livelihood of millions of market vendors, farmers, and transporters. This leads to some very important research questions. First, *how does the structure of food supply chains affect the likelihood of zoonotic disease spread? Can zoonotic risk be lowered with less severe supply chain restructuring than closing live animal markets?* Second, *are there management interventions at the market, farm, and slaughterhouse level that can effectively reduce zoonotic disease spread?*

[4] China detects a large quantity of novel coronavirus at Wuhan seafood market. http://www.xinhuanet.com/english/2020-01/27/c_138735677.htm

[5] 45 people and 40 environmental samples in Beijing Xinfadi Market tested positive for COVID19 https://www.thepaper.cn/newsDetail_forward_7829082

There is evidence, for instance, that certain markets in China are riskier than others. In Gao et al. [2020] food safety risk scores are created for all markets in China, based on unsupervised clustering of CFDA food safety tests to specific markets, and it is shown that these food safety risk scores are predictive of zoonotic disease outbreaks. Furthermore, it is shown that higher-risk markets are more likely to have news about management and environmental issues such as sanitation problems, which provides support for the hypothesis that management interventions may be helpful to prevent zoonotic disease spread. Because of the enormous health impact of these pandemics and the risk for future pandemics from zoonotic viruses such as avian flu (H5N1, H7N9) described by Osterholm [2005], this could be a very impactful research direction that complements the more widespread work in the OR community on pandemic response.

5 Managing Food Waste in Supply Chains

The Food and Agriculture Organization of the United Nations (FAO) estimates that one-third of the world's food is lost or wasted each year [Gustavsson et al., 2011]. Food waste results in negative externalities including impacts on global warming, global food insecurity, and loss of efficiency in food supply chains. For these reasons, reducing food loss is a global priority: Goal 12.3 of the FAO's 2030 Agenda for Sustainable Development is to "halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses" by 2030 [UN, 2015].

Food waste has far-reaching consequences on the environment, both in terms of wasted resources and greenhouse gas emissions. FAO [2015] notes that if food waste were a country, it would be the third-largest emitter of greenhouse gases. Additionally, food waste strains the entire food supply chain. It is estimated that grocery stores in the U.S. lose $18.2 billion per year due to wasted goods [Serafino, 2018]. At the farm level, particularly for small and mid-size farmers whose profit margins are already thin, the loss of perfectly edible crops due to external economic and environmental factors can be damaging to the farm's financial viability [Hoppe, 2014]. However, perhaps the most concerning consequence of food waste is the missed opportunity to use this surplus to provide nutrients to food-insecure households across the globe. This will be discussed in more detail in the following section.

Because the reasons for, and extend of, food waste can vary drastically across regions and food groups, this section will focus specifically on fruit and vegetable food waste in U.S. supply chains. Overall in the U.S., about 40% of food produced goes uneaten [Gunders and Bloom, 2017]. Furthermore, about 52% of fruits and vegetables grown each year are lost or wasted, although this number can vary widely depending on the crop [Gunders and Bloom, 2017][6]. Twenty-eight percent

[6]It should be noted that this estimate is based on limited data, and is a collective estimate for the U.S., Canada,

of fruits and vegetables are lost during production (including farming), 12% during distribution and retail, and 28% at the consumer level [Gunders and Bloom, 2017]. In what follows, a brief overview of the reasons for, and efforts to reduce, food loss and waste at the retail and production levels of the supply chain is presented[7].

5.1 Challenges

Defining and measuring food waste. One fundamental difficulty in overcoming food loss/waste is the lack of standard definitions of these terms [Bellemare et al., 2017]. For example, some definitions consider food loss to include all edible food that is not eaten, whereas other definitions only include food that is not used for a productive purpose [Bellemare et al., 2017]. Furthermore, although food waste and food loss are colloquially used interchangeably, FAO distinguishes between the two, considering "loss" to be food that is lost between post-harvest and the retail level, whereas "waste" describes food that is lost or discarded at the retail and consumer levels of the supply chain [FAO, 2019]. Bellemare et al. [2017] discuss the differences between, and limitations of, various definitions of food waste. For the remainder of this section, FAO's distinction between food loss and waste is adopted.

The lack of available data at certain levels of the supply chain, or certain regions, makes measuring food waste and food loss a difficult task. Estimates of food waste can vary drastically depending on the location and type of food. Waste and loss are typically largest for fruits and vegetables and smallest for non-perishable items [FAO, 2019, Gunders and Bloom, 2017]. This section focuses specifically on fruit and vegetable food loss/waste in the U.S.

Compared to other levels of the supply chain, relatively little is known about the extent of farm-level food waste, due in part to a lack of data. Although the National Agricultural Statistical Services asks farmers about acres planted and harvested of various crops in annual surveys, this information is not published in detail and does not explicitly contain food waste estimates. Furthermore, it is unlikely that this survey data is reliable—farmers do not typically have incentives to keep track of the amount of crops that they do *not* harvest. Therefore, farmers will provide rough estimates of these figures to complete the surveys[8].

Despite the lack of large-scale data, estimates of farm-level food waste do exist. These estimates are generally based on small-scale studies, focusing on a handful of farmers and a small number of crops. Kantor et al. [1997] estimate that 7% of crops that are planted are never harvested (this includes non-fruits and vegetables), FAO estimates that 28% fruits and vegetables are lost during production (including farming), and Feeding America estimates that at least 6 billion pounds of

Australia, and New Zealand [Gunders and Bloom, 2017].

[7]We do not focus on consumer-level food waste, as research in this area is more closely related to psychology and marketing rather than operations

[8]Based on the fourth author's conversations with farmers in Massachusetts and New Hampshire.

fresh produce are not harvested each year by analyzing six specific crops [Gunders and Bloom, 2017]. While these rough estimates give us an idea of the extent of the problem, they do not provide a rigorous or detailed understanding of the problem on large-scale.

Competing incentives and causes of waste. Understanding and incorporating the incentives of supply chain entities is critical to developing strategies to combat food waste. Food loss on farms occurs for many complex reasons. Natural phenomena, such as weather and pests, lead to large fluctuations in the availability of certain crops from year to year. Especially in years with larger-than-normal yields, the surplus crop may go unharvested for a variety of reasons. Wholesale price fluctuations, timing constraints caused by perishability, yield and quality uncertainty, suboptimal forecasting, and labor shortages may incentivize a farmer to leave certain acres of crops unharvested [Johnson et al., 2019]. Specifically, if the farmer believes that he is unlikely to make a profit on a certain crop, or if another crop is more valuable, the farmer will divert his limited resources—in particular, labor—to a more promising crop [Johnson et al., 2019].

At the retail level, common strategies used to increase demand/sales may also increase food waste. For example, in order to keep shelves fully stocked with fresh produce throughout the day, retailers must 1) retain safety stocks of inventory to avoid stock-outs, and 2) pull perfectly edible produce nearing expiration from the shelves. These strategies—while potentially increasing profits—lead to increased food waste [Gunders and Bloom, 2017].

5.2 Research Directions and Opportunities

Food waste at the retail level. In the operations management literature, retail-level food waste is an emerging topic. By developing and analyzing a stylized model, Belavina et al. [2017] compare two different revenue models for online grocery retailers, and, in part, consider their impact on food waste. Belavina [2020] consider how the density of grocery retail locations impacts food waste by developing and studying a two-echelon supply chain model. Akkas and Honhon [2020] study the impact of different inventory shipment policies (e.g., shipping the oldest inventory first) on food waste by formulating the problem as a dynamic program motivated by an empirical analysis of real-world data. Li et al. [2017] consider how the packaging of goods at food retailers can impact waste by developing a model of consumer purchasing behavior which includes a strategic response to the retailer's choice of packaging. This literature has begun to explore how tools from OR and advanced analytics can help inform our understanding of and prevent food waste. There are many future directions for this work, including the development and analysis of new creative interventions for reducing food waste in grocery stores. For example, future research could explore how freshness differentiation and dynamic pricing schemes could incentivize consumers to purchase a product that is closer to expiration.

Food loss at the farm level. A body of existing OR research considers optimizing processes and programs that have could have an indirect impact on farm-level food waste. Ata et al. [2016] optimize the volunteer management operations of a gleaning organization—a non-profit that organizes volunteer trips to harvest and donate crops that would otherwise be wasted. Another possible strategy for reducing food waste on farms is through better contracting and revenue protection. By developing a model of farmer behavior calibrated with U.S. Department of Agriculture (USDA) data, Alizamir et al. [2018] study the impact of two government subsidy programs on farmer behavior (in terms of acres planted), social welfare, and government spending. Federgruen et al. [2019] study contract farming by developing and analyzing a Stackelberg game-theoretic model in which a manufacturer who must determine a menu of contracts to offer to a set of farmers. Although this literature does not directly attempt to reduce food waste, the impact of this stream of research could greatly benefit farmers and have the effect of reducing food waste.

Connection to food insecurity. Food waste is closely tied to food insecurity. Many efforts aimed at reducing food waste focus on re-routing food that would otherwise be wasted to people in need. Matching surplus supply of fruits and vegetables to demand sources is a particularly difficult problem that is well-suited to OR research methods. Research in this area is discussed in Section 6.2.

6 Managing Food Security, Food Deserts, and The Diet Disparity

The United Nations (UN) reports that 8.9% of the global population is undernourished [FAO, IFAD, UNICEF, WFP and WHO, 2020]. This is an increase of 60 million people from 2014-2019 and does not include the likely further increase due to the COVID-19 pandemic [FAO, IFAD, UNICEF, WFP and WHO, 2020]. Furthermore, 25.9% of the global population experienced hunger at some point in 2019. This phenomenon—disruption in either the quality or quantity of food consumed—is known as *food insecurity*. Food insecurity, through its impact on diet quality, exacerbates health risks and inflates healthcare costs. The UN estimates that over 1.5 billion people cannot afford a nutritionally sound diet [FAO, IFAD, UNICEF, WFP and WHO, 2020].

Although food insecurity and hunger are most prevalent in developing countries, these issues are nonetheless salient in the U.S.. In 2019, 10.9% of the U.S. households were food insecure [USDA Economic Research Services, 2019]. Furthermore, Americans consume far fewer fruits and vegetables than the recommended daily amount. The link between lack of sufficient fruit and vegetable consumption and life-threatening chronic conditions, such as cardiovascular diseases and obesity, is well established [Morland et al., 2006].

Low fruit and vegetable consumption, and poor diets more generally, are particularly prevalent issues among underserved populations [Darmon and Drewnowski, 2008]. This socioeconomic difference in diet is often referred to as *the diet disparity*. Establishing effective policy strategies for increasing the healthfulness of diets, especially among low-income households, is a national priority with a substantial federal budget investment of over $60 billion each year[9]. Although it is clear that the diet disparity is a serious issue, the reasons for the disparity are debated. Healthy foods are generally more expensive than unhealthy alternatives, and therefore the price is likely to play a role [Drewnowski, 2010]. Certain interventions are specifically aimed at providing consumers with greater purchasing power or decreasing the price of healthy options. Furthermore, nutrition education or information is also likely an important factor. Finally, and more recently, emphasis has been placed on the role of the local food environment in contributing to the diet disparity. *Food deserts* are defined as census tracts in the U.S.. where the majority of households have poor access to grocery stores [USDA ERS, 2017]. In food deserts, fruit and vegetable consumption is particularly low [Gustafson et al., 2016]. This has prompted policymakers to consider interventions aimed at increasing access to grocery stores in food desert areas.

6.1 Current Policy Interventions in the U.S.

Price-related interventions are perhaps the most commonly used and highly studied type of demand-side lever in food policy. The Supplemental Nutrition Assistance Program (SNAP)—formerly the food stamp program—is the largest example of a price-related policy lever, with an annual budget of around $60 billion [USDA, 2017]. Many other types of price-related policy levers exist, including those that specifically subsidize or incentivize healthy food purchasing (e.g., The Special Supplemental Nutrition Program for Women, Infants, and Children, and The Healthy Incentives Program in Massachusetts). Price-related interventions are generally found to be successful at increasing the healthfulness of diets, but only to a certain extent and with some caveats [Dong and Lin, 2009]. For example, SNAP's impact on the diet is still debated Leung et al. [2014].

Food banks and food pantries address the price issue by offering free food items to low-income consumers. Bazerghi et al. [2016] perform a systematic review of the relationship between food banks and food insecurity, concluding that although food banks/pantries play a critical role in assisting food insecure households, their capacity and overall volume—particularly of nutrient-dense perishable foods like fruits and vegetables—is not large enough to substantially improve overall food insecurity.

Numerous analyses have concluded that nutrition education (or nutritional attitudes, values,

[9] The SNAP budget itself is around $60 billion/year [USDA, 2017]. This does not include funding for other federal food policy programs including SNAP-Ed (a nutrition education program) and the Healthy Food Financing Initiative (a program aimed at improving access to healthy food).

beliefs, etc.) impacts diet. Spronk et al. [2014] performs a meta-analysis of studies on the relationship between nutrition education (or nutritional attitudes, values, beliefs, etc.) on diet, and conclude that there is generally a positive relationship with fruit and vegetable consumption, but the association is typically weak, and the effect can vary widely across programs.

Since 2014, the Healthy Food Financing Initiative has distributed over $220 million dollars to community-based projects supporting increased access to healthy food in low-income food deserts [The Reinvestment Fund, 2019]. Strategies include building new grocery stores and increasing the stock of healthy food at convenience or corner stores. Despite their rise in popularity, the effect of access-related interventions on diet is not well established [Allcott et al., 2019, Ver Ploeg and Rahkovsky, 2016]. Many case studies that evaluate the impact of new grocery stores on food desert residents' diets have reached mixed conclusions, often finding no average impact on fruit and vegetable consumption [Cummins et al., 2014, 2005, Wrigley et al., 2003]. These findings give rise to new research questions, many of which could be addressed using advanced analytical tools. For example: *Are access interventions most impactful for certain subgroups? How can retail outlets be incentivized to stock healthier and fresher foods?*

Meal delivery services are a promising intervention for supplying healthy meals to households who have difficulty reaching grocery stores. Meals on Wheels, which started in the 1950s, combats hunger among seniors in need by delivering ready-made meals to their front door [Meals on Wheels America, 2021]. Medically tailored meal delivery services—a specific type of meal delivery program that provides nutrient-specific meals to low-income individuals with chronic diseases—have been found to improve health and reduce food insecurity [Berkowitz et al., 2019]. These programs motivate several interesting research questions related to intervention design, personalization, and routing.

6.2 Research Directions and Opportunities

In what follows, relevant OR research topics will be classified into three categories: transportation and logistics, resource allocation, and methodological research.

Transportation and logistics. Food distribution is a specialized version of classical OR problems in resource allocation and routing. A body of research considers the problem of food transportation and routing for non-profit organizations [Eisenhandler and Tzur, 2019, Yildiz et al., 2013, Solak et al., 2014, Davis et al., 2014, Balcik et al., 2014]. Eisenhandler and Tzur [2019] formulate a food bank's routing and resource allocation problem as an optimization problem whose objective is to delivery as much food as possible while ensuring that the amounts delivered to each location are equitable. Yildiz et al. [2013] address the problem of delivering meals to homes (i.e., the Meals on Wheels problem) by developing a memetic algorithm that includes the facility location problem, demand assignment problem, and routing problem. Solak et al. [2014] develop a mixed-integer program to solve a similar location–assignment–routing problem, and propose solution methods based on Bender's decomposition. Davis et al. [2014] propose a set-covering algorithm to assign "agencies" (e.g., food banks or pantries) to food delivery points, taking into consideration capacity and spoilage constraints. Finally, Balcik et al. [2014] propose a set-covering method to solve the donation routing problem with the objective of minimizing waste and ensuring equity in donation deliveries. In the routing and transportation domain, new problems are continuing to emerge. For example, mobile markets are emerging as a new outlet for purchasing fresh food. Optimal routes for mobile markets, taking fairness into consideration, is an interesting area for future OR research.

Volunteer coordination and matching is another important logistical component for many food rescue and distribution non-profit organizations. Manshadi and Rodilitz [2020] and Lo et al. [2021] consider the problem of crowd-sourcing volunteers and matching them to time-sensitive jobs such as food recovery and delivery. Manshadi and Rodilitz [2020] develop a model of volunteer behavior to determine the optimal online volunteer nudging strategy. Lo et al. [2021] formulate the problem of matching volunteers to food delivery routes as a repeated two-sided market matching problem, and study the optimal assignment policy.

Resource allocation. Resource allocation problems include both the allocation of food donations to demand sources, as well as the allocation of resources (e.g., money) to food policy programs. As mentioned in the previous section, some literature (e.g., Eisenhandler and Tzur [2019] and Balcik et al. [2014]) couples the food allocation problem and transportation/routing problem together. Additional research focuses solely on the food allocation problem.

Non-profit food allocation problems are studied in Lien et al. [2014], Orgut et al. [2016] and Fianu and Davis [2018]. Through a dynamic programming framework, Lien et al. [2014] consider a sequential resource allocation problem for a non-profit that strives for equity in outcomes. Fianu and Davis [2018] consider an equity-based objective for a resource allocation problem with uncertain supply and deterministic demand, proposing a Markov decision process modeling approach. Orgut et al. [2016] consider a food bank distribution problem where the primary objective is to achieve equity in the allocation. The authors develop network flow models to solve the allocation problem.

While the aforementioned literature considers food allocation, budget allocation is another critical food policy problem. Levi et al. [2019] study the problem a central planner who must allocate its budget to different food policy interventions in order to maximize fruit and vegetable consumption for a low-income consumer. This work is related to the broader OR literature on optimal subsidies that has been applied to a variety of humanitarian contexts (e.g. Taylor and Xiao [2019], Levi et al. [2016], Yu et al. [2018], Alizamir et al. [2016]). There are many future research opportunities in food policy intervention optimization. For example, future research could consider how to implement more personalized intervention programs in practice and the robustness of such strategies.

Methodological research. New methodological research could greatly expand the available toolbox for optimizing policy interventions in application areas such as food policy. A key difficulty in improving the efficacy of food policy interventions is the limitation imposed by most data sets. Namely, data is generally "small" and observational. For example, perhaps the most detailed dataset in this space is the USDA's Food Acquisition and Purchase Survey dataset [Economic Research Service, USDA, 2020]. This is the only publicly available dataset in the U.S. that contains detailed information on household food purchases, demographics, and the local food environment. However, this dataset has its weaknesses. Namely, it only contains one week's worth of food purchasing data for each household and contains fewer than 5,000 households.

Because of data limitations, understanding which interventions are most effective, and for whom, is a key difficulty. Yet, gaining this understanding is critical for improving policies. In the "optimizing interventions" literature discussed above, the researchers generally take a structured modeling approach to understanding counterfactuals. Namely, the researcher assumes that individuals make decisions according to a certain model, and counterfactuals are understood with respect to these models.

However, new data-driven approaches using "small data" have been emerging that offer a different approach for understanding and estimating causal effects. Gupta et al. [2020] consider the problem of allocating a binary intervention amongst individuals in a population, subject to a budget constraint. In Gupta et al. [2020], the authors' goal is to determine the subpopulation that would be most impacted by the treatment and propose a new method that uses only summary statistics that are often found in published studies. Although Gupta et al. [2020] focuses on a healthcare setting, the methods could be applied to a variety of settings where large data sets are not available, but summary data is widely available. This is often the case for food policy initiatives. Developing additional methods for personalizing interventions in "small data" regimes in a promising area for future research.

7 Conclusion

In the past few years, various global trends have put increasing pressure on global food supply chains and shed light on vulnerabilities that may jeopardize the ability to provide healthy, nutritious foods to the global population. Growing demand for food and product diversity has to led a complex network of farmers, manufacturers, distributors, and retailers though with little quality surveillance. Opaqueness across the food supply chain, together with technical challenges related to the collection, cleaning, processing, and integration of data means that there is little insight into the distributions of risks across the supply chain. Understanding risks is critical to informing decisions that could reduce food adulteration and waste. Moreover, next-generation food systems need to be designed in ways that balance the need to provide healthy, affordable foods to a growing population, while ensuring the livelihoods of those employed in the agricultural sector and mitigating climate change and ecologic footprint.

The paper outlines the myriad ways in which data-driven analytical tools can be used to inform decisions in food supply chains, especially in a resource-constrained environment and when dealing with heterogeneous products. The scale of the food supply chain, as well as accompanying data, means that advanced and automated tools are needed to effectively monitor risks throughout the supply chain. These data platforms can then be leveraged to build various optimization and predictive models that help design and evaluate trade-offs between different interventions. Building on the United Nations Sustainable Development Goals, in particular *Goal 2: End hunger, achieve, food security and improved nutrition and promote sustainable agriculture*, the 2021 Food Systems Summit aims to galvanize stakeholders towards concerted efforts to make food supply chains more sustainable. The use of analytics and sensing technologies, together with regulatory science, can help foster a new era in which food systems are safer and supply chains are more resilient. Increasingly, tools needed to drive risk-based decision-making are becoming available. However, substantial research opportunities remain. Implementing new tools across the food supply chain, from farmers to consumers, will be key to move towards more sustainable practices that proactively meet the needs of people and the planet.

Acknowledgement

The work of the fifth author was partially supported by a grant award from the Walmart Foundation.

References

H.C.J. Godfray, P. Aveyard, T. Garnett, J.W. Hall, T.J. Hall, J. Lorimer, R.T. Pierrehumbert, P. Scarborough, M. Springmann, and S.A. Jebb. Meat consumption, health, and the environment. *Science*, 361(6399), 2018.

U.S. Food and Drug Administration. Fda strategy for the safety of imported food. Online, 2019. URL https://www.fda.gov/media/120585/download.

Eva-Marie Meemken and Marc F Bellemare. Smallholder farmers and contract farming in developing countries. *PNAS*, 117(1):259–264, 2019.

A.H. Havelaar, M.D. Kirk, P.R. Torgerson, H.J. Gibb, T. Hald., R.J. Lake, N. Praet, D.C. Bellinger, N.R. de Silva, N. Gargouri, N. Speybroeck, A. Cawthorne, C. Mathers, C. Stein, F.J. Angulo, B. Devleesschauwer, and World Health Organization Foodborne Disease Burden Epidemiology Reference Group 2015. World health organization global estimates and regional comparisons of the burden of foodborne disease in 2010. *PLoS medicine*, 12(12), 2015.

S. Jaffee, S. Henson, L. Unnevehr, D. Grace, and E. Cassou. *The Safe Food Imperative : Accelerating Progress in Low- and Middle-Income Countries; Agriculture and Food Series*. The World Bank, Washington, DC, 2019.

E. Abebe, G. Gugsa, and M. Ahmed. Review on major food-borne zoonotic bacterial pathogens. *Journal of tropical medicine*, 2020(4674235), 2020.

RG Webster. Wet markets–a continuing source of severe acute respiratory syndrome and influenza? *Lancet*, 363(9404):234–236, 2004.

Lorena Ruiz and Avelino Alvarez-Ordonez. The role of the food chain in the spread of antimicrobial resistance (AMR). In *Functionalized Nanomaterials for the Management of Microbial Infection: A Strategy to Address Microbial Drug Resistance*, pages 23–47. Elsevier, 2017.

FAO and IFAD and UNICEF and WFP and WHO. The state of food security and nutrition in the world 2020. Online, 2020. URL http://www.fao.org/3/ca9692en/CA9692EN.pdf.

FAO, IFAD, UNICEF, WFP and WHO. *The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets*. FAO, Rome, 2020. URL https://doi.org/10.4060/ca9692en.

FAO. *Food wastage footprint: Full cost accounting*. FAO, Rome, 2014.

P.J. Gerber, H. Steinfeld B. Henderson, A. Mottet, C. Opio, J. Dijkman, A. Falcucci, and G. Tempio. *Tackling Climate Change through Livestock: A global assessment of emissions and mitigation opportunities*. FAO, Rome, 2013.

Philop Bernstein and Laura Haas. Information integration in the enterprise: A guide to the tools and core technologies for merging information from disparate sources. *Communications of the ACM*, 51(9):72–79, 2008.

U.S. Food and Drug Administration. New era of smarter food safety: Fda's blueprint for the future. Online, 2020. URL https://www.fda.gov/media/139868/download.

Lawrence M. Wein and Yifan Liu. Traceability in a food supply chain: Safety and quality perspectives. *PNAS*, 102(38):9984–9989, 2005.

US FDA. Milestones in u.s. food and drug law history, 2018. URL https://www.fda.gov/about-fda/fdas-evolving-regulatory-powers/milestones-us-food-and-drug-law-history.

U.S. FDA. Import Alerts. https://www.fda.gov/forindustry/importprogram/actionsenforcement/importalerts/default.htm, 2018.

E.U. Opara. The effect of information technology on global business. *Journal for International Business and Entrepreneurship Development*, 2(1):45–49, 2003.

Cangyu Jin, Retsef Levi, Qiao Liang, Nicholas Renegar, Stacy Springs, Jiehong Zhou, and Weihua Zhou. Testing at the source: Analytics-enabled risk-based sampling of food supply chains in china. *Management Science*, 2021. https://pubsonline.informs.org/doi/10.1287/mnsc.2020.3839.

J. E. Hobbs. Information asymmetry and the role of traceability system. *Agribusiness*, 20(4): 397–415, 2004.

J.E. Hobbs, D. Bailey, D.L. Dickinson, and M. Haghiri. Traceability in the Canadian red meat sector: Do consumers care? *Canadian Journal of Agricultural Economics*, 53(1):47–65, 2005.

S. Pouliot and D. A. Sumner. Traceability, liability, and incentives for food safety and quality. *American Journal of Agricultural Economics*, 90(1):15–27, 2008.

S. A. Starbird and V. Amanor-Boadu. Do inspection and traceability provide incentives for food safety? *Journal of Agricultural and Resource Economics*, 31(1):14–26, 2006.

B. Racino. Flood of food imported to U.S., but only 2 percent inspected. http://www.nbcnews.com/id/44701433/ns/health-food_safety/t/flood-food-imported-us-only-percent-inspected/%23.WPff9Pnytpg, 2011.

Sarah K. Lowder, Jakob Skoet, and Terri Raney. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Development*, 87:16–29, 2016.

HFG. Flood of food imported to U.S., but only 2 percent inspected. www.hfgip.com%2Fsites%2Fdefault%2Ffiles%2Flaw%2Ffood_safety_-_16.02.2016.pdf, 2016.

European Commission. RASFF - Food and Feed Safety Alerts. https://ec.europa.eu/food/safety/rasff_en, 2019.

U.S. FDA. Remarks by Frank Yiannas to the International Association for Food Protection, Louisville, 2019. https://www.fda.gov/news-events/speeches-fda-officials/remarks-frank-yiannas-international-association-food-protection-louisville-07222019.

U.S. FDA. New Era of Smarter Food Safety. https://www.fda.gov/food/new-era-smarter-food-safety, 2021.

Xinhua News Agency. Opinions of the central committee of the communist party of china and the state council on deepening reform and strengthening food safety. http://www.gov.cn/zhengce/2019-05/20/content_5393212.htm, 2019.

U.S. Government Accountability Office GAO. Imported food safety: Fda's targeting tool has enhanced screening, but further improvements are possible. https://www.gao.gov/products/GAO-16-399, 2016.

Kiran Kate, Sneha Chaudhari, Andy Prapanca, and Jayant Kalagnanam. FoodSIS: a text mining system to improve the state of food safety in Singapore. pages 1709–1718, 2014.

Yang Liu, Feiyan Liu, Jianfang Zhang, and Jianbo Gao. Insights into the nature of food safety issues in Beijing through content analysis of an internet database of food safety incidents in China. *Food Control*, 51:206–211, 2015.

Aiping Liu, Li Shen, Yuxi Tan, Zhenghai Zeng, Yuntao Liu, and Cheng Li. Food integrity in china: Insights from the national food spot check data in 2016. *Food Control*, 84:403–407, 2017.

Sivaranjani Pagadala, Sasha C. Marine, Shirley A. Micallef, Fei Wang, Donna M. Pahl, Meredith V. Melendez, Wesley L. Kline, Ruth A. Oni, Christopher S. Walsh, Kathryne L. Everts, and Robert L. Buchanan. Assessment of region, farming system, irrigation source and sampling time as food safety risk factors for tomatoes. *International Journal of Food Microbiology*, 196:98 – 108, 2015.

GA Kleter and HJ Marvin. Indicators of emerging hazards and risks to food safety. *Food and Chemical Toxicology*, 47(5):1022–1039, 2009.

H. J. Marvin, Y. Bouzembrak, E. M. Janssen, H. v. van der Fels-Klerx, E. D. van Asselt, and G. A Kleter. A holistic approach to food safety risks: Food fraud as an example. *Food Research International*, 89:463–470, 2016.

K. Verhaelen, A. Bauer, F. Gunther, B. Muller, M. Nist, B. Ulker Celik, C. Weidner, H. Kuchenhoff, and P. Wallner. Anticipation of food safety and fraud issues: Isar - a new screening tool to monitor food prices and commodity flows. *Food Control*, 94:93–101, 2018.

Yu Zhang. Food safety risk intelligence early warning based on support vector machine. *Journal of Intelligent & Fuzzy Systems*, 38(6):6957–6969, 2020.

Y. Huang, R. Levi, S. Springs, S. Wang, and Y. Zheng. Risk drivers for economically motivated food adulteration in China's farming supply chains. *Annals of Mathematical Statistics*, 19:279–281, 2018.

V. Babich and C. S. Tang. Managing opportunistic supplier product adulteration: Deferred payments, inspection, and combined mechanisms. *Manufacturing & Service Operations Management*, 14(2):301–314, 2012.

Retsef Levi, Nicholas Renegar, Stacy Springs, and Tauhid Zaman. Supply chain network analytics guiding food regulatory operational policy. *Working Paper*, 2020. Available at SSRN: https://ssrn.com/abstract=3374620.

Z. Wang, van der Fels-Klerx H. J., and A. G. J. M. Oude Lansink. Optimization of sampling for monitoring chemicals in the food supply chain using a risk based approach: The case of aflatoxins and dioxins in the dutch dairy chain. *Risk Analysis*, 40:2439–2560, 2020.

CDC. More people in the us dying from antibiotic-resistant infections than previously estimated. https://www.cdc.gov/media/releases/2019/p1113-antibiotic-resistant.html, 2019.

Ross S. McInnes, Gregory E. McCallum, Lisa E. Lamberte, and Willem van Schaik. Horizontal transfer of antibiotic resistance genes in the human gut microbiome. *Current Opinion in Microbiology*, 53:35–43, 2020.

Yi Yun Liu, Yang Wang, Timothy R. Walsh, Ling Xian Yi, Rong Zhang, James Spencer, Yohei Doi, Guobao Tian, Baolei Dong, Xianhui Huang, Lin Feng Yu, Danxia Gu, Hongwei Ren, Xiaojie Chen, Luchao Lv, Dandan He, Hongwei Zhou, Zisen Liang, Jian Hua Liu, and Jianzhong Shen. Emergence of plasmid-mediated colistin resistance mechanism mcr-1 in animals and human beings in china: A microbiological and molecular biological study. *The Lancet Infectious Diseases*, 16:161–168, 2016.

Steve Hinchliffe, Andrea Butcher, and Muhammad Meezanur Rahman. The AMR problem: demanding economies, biological margins, and co-producing alternative strategies. *Palgrave Communications*, 4:1–12, 2018.

Maya Nadimpalli, Elisabeth Delarocque-Astagneau, David C. Love, Lance B. Price, Bich Tram Huynh, Jean Marc Collard, Kruy Sun Lay, Laurence Borand, Awa Ndir, Timothy R. Walsh, Didier Guillemot, Agathe De Lauzanne, Alexandra Kerleguer, Arnaud Tarantola, Patrice Piola, Thida Chon, Siyin Lach, Veronique Ngo, Sok Touch, Zo Zafitsara Andrianirina, Muriel Vray, Vincent Richard, Abdoulaye Seck, Raymond Bercion, Amy Gassama Sow, Jean Baptiste Diouf, Pape Samba Dieye, Balla Sy, Bouya Ndao, Maud Seguy, Laurence Watier, and Armiya Youssouf Abdou. Combating global antibiotic resistance: Emerging one health concerns in lower-and middle-income countries. *Clinical Infectious Diseases*, 66:963–969, 2018.

US FDA. The national antimicrobial resistance monitoring system strategic plan 2021-2025, 2020. URL https://www.fda.gov/animal-veterinary/antimicrobial-resistance/national-antimicrobial-resistance-monitoring-system.

Thomas P. Van Boeckel, Joao Pires, Reshma Silvester, Cheng Zhao, Julia Song, Nicola G. Criscuolo, Marius Gilbert, Sebastian Bonhoeffer, and Ramanan Laxminarayan. Global trends in antimicrobial resistance in animals in low- and middle-income countries. *Science*, 365, 2019.

Matthew T.G. Holden, Li Yang Hsu, Kevin Kurt, Lucy A. Weinert, Alison E. Mather, Simon R. Harris, Birgit Strommenger, Franziska Layer, Wolfgang Witte, Herminia De Lencastre, Robert Skov, Henrik Westh, Helena Zemlickova, Geoffrey Coombs, Angela M. Kearns, Robert L.R. Hill, Jonathan Edgeworth, Ian Gould, Vanya Gant, Jonathan Cooke, Giles F. Edwards, Paul R. McAdam, Kate E. Templeton, Angela McCann, Zhemin Zhou, Santiago Castillo-Ramirez, Edward J. Feil, Lyndsey O. Hudson, Mark C. Enright, Francois Balloux, David M. Aanensen, Brian G. Spratt, J. Ross Fitzgerald, Julian Parkhill, Mark Achtman, Stephen D. Bentley, and Ulrich Nubel. A genomic portrait of the emergence, evolution, and global spread of a methicillin-resistant staphylococcus aureus pandemic. *Genome Research*, 23:653–664, 2013.

Michael Baym, Tami D. Lieberman, Eric D. Kelsic, Remy Chait, Rotem Gross, Idan Yelin, and Roy Kishony. Spatiotemporal microbial evolution on antibiotic landscapes. *Science*, 353:1147–1151, 2016.

China MoA. Announcement for the 2019 antimicrobial resistance monitoring plan of bacteria from animal source, 2019. URL http://www.moa.gov.cn/gk/tzgg_1/tz/201903/t20190328_6177403.htm.

Cangyu Jin, Retsef Levi, Qiao Liang, Nicholas Renegar, and Jiehong Zhou. Food safety and the adoption of traceability: Evidence from a wholesale market field survey in china. *Working Paper*, 2019. Available at SSRN: https://ssrn.com/abstract=3497135.

Ya He, Qingbin Yuan, Jacques Mathieu, Lauren Stadler, Naomi Senehi, Ruonan Sun, and Pedro J.J. Alvarez. Antibiotic resistance genes from livestock waste: occurrence, dissemination, and treatment. *NPJ Clean Water*, 3:1–11, 2020.

Luria Leslie Founou, Raspail Carrel Founou, and Sabiha Yusuf Essack. Antibiotic resistance in the food chain: A developing country-perspective. *Frontiers in Microbiology*, 7:1881, 2016.

Carlos Chique, John Cullinan, Brigid Hooban, and Dearbhaile Morris. Mapping and analysing potential sources and transmission routes of antimicrobial resistant organisms in the environment using geographic information systems—an exploratory study. *Antibiotics*, 8, 2019.

Maria Victoria Grosso-Becerra, Christian Santos-Medellin, Abigail Gonzalez-Valdez, Jose Luis Méndez, Gabriela Delgado, Rosario Morales-Espinosa, Luis Servin-Gonzalez, Luis David Alcaraz, and Gloria Soberon-Chavez. Pseudomonas aeruginosa clinical and environmental isolates constitute a single population with high phenotypic diversity. *BMC Genomics*, 15, 2014.

Michael Lingzhi Li, Hamza Tazi Bouardi, Omar Skali Lami, Thomas A. Trikalinos, Nikolaos K. Trichakis, and Dimitris Bertsimas. Forecasting covid-19 and analyzing the effect of government interventions. *medRxiv*, 2020. URL https://www.medrxiv.org/content/early/2020/06/24/2020.06.23.20138693.

Christopher L.F. Sun, Eugenio Zuccarelli, El Ghali A. Zerhouni, Jason Lee, James Muller, Karen M. Scott, Alida M. Lujan, and Retsef Levi. Predicting coronavirus disease 2019 infection risk and related risk drivers in nursing homes: A machine learning approach. *Journal of the American Medical Directors Association*, 21(11):1533 – 1538.e6, 2020.

Nature Food Editors. Exploring wet markets. *Nature Food*, 1:241, 2020. URL https://doi.org/10.1038/s43016-020-0090-1.

Y Guan, BJ Zheng, YQ He, XL Liu, ZX Zhuang, CL Cheung, SW Luo, Li. PH, LJ Zhang, YJ Guan, KM Butt, KL Wong, KW Chan, W Lim, KF Shortridge, KY Yuen, JS Peiris, and LL Poon. Isolation and characterization of viruses related to the SARS coronavirus from animals in southern China. *Science*, 302(5643):276–278, 2003.

SS Lee, NS Wong, and CC Leung. Exposure to avian influenza h7n9 in farms and wet markets. *Lancet*, 381(9880):1815, 2013.

PC Woo, SK Lau, and KY Yuen. Infectious diseases emerging from Chinese wet-markets: zoonotic origins of severe respiratory viral infections. *Curr Opin Infect Dis*, 19(5):401–407, 2006.

S Neuman. U.s. pressures china to close wet markets thought to be source of covid-19, 2020. Availablefrom:https://www.npr.org/sections/coronavirus-live-updates/2020/04/23/842178010/u-s-pressures-china-to-close-wet-markets-thought-to-be-source-of-covid-19.

Jennifer Gao, Retsef Levi, and Nicholas Renegar. The link between food safety and zoonotic disease risks at wholesale and wet markets in china. *Working Paper*, 2020. Available at SSRN: https://ssrn.com/abstract=3718510.

Michael T. Osterholm. Preparing for the next pandemic. *The New England Journal of Medicine*, 352:1839–1842, 2005.

Jenny Gustavsson, Christel Cederberg, Ulf Sonesson, Robert Van Otterdijk, and Alexandre Meybeck. Global food losses and food waste, 2011.

UN. *Transforming Our World: The 2030 Agenda for Sustainable Development*. New York, 2015.

FAO. *Food wastage footprint and climate change*. FAO, Rome, 2015.

Melody Serafino. Press release: Refed analysis reveals food waste represents $18.2 billion profit opportunity for food retailers. Technical report, ReFED, 2018.

Robert A Hoppe. Structure and finances of US farms: Family farm report, 2014 edition. 2014.

Dana Gunders and Jonathan Bloom. *Wasted: How America is losing up to 40 percent of its food from farm to fork to landfill*. Natural Resources Defense Council New York, 2017.

Marc F Bellemare, Metin Çakir, Hikaru Hanawa Peterson, Lindsey Novak, and Jeta Rudi. On the measurement of food waste. *American Journal of Agricultural Economics*, 99(5):1148–1158, 2017.

FAO. *The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction*. FAO, Rome, 2019.

Linda Scott Kantor, Kathryn Lipton, Alden Manchester, and Victor Oliveira. Estimating and addressing america's food losses. *Food Review/National Food Review*, 20(1482-2016-121447): 2–12, 1997.

Lisa K Johnson, J Dara Bloom, Rebecca D Dunning, Chris C Gunter, Michael D Boyette, and Nancy G Creamer. Farmer harvest decisions and vegetable loss in primary production. *Agricultural Systems*, 176:102672, 2019.

Elena Belavina, Karan Girotra, and Ashish Kabra. Online grocery retail: Revenue models and environmental impact. *Management Science*, 63(6):1781–1799, 2017.

Elena Belavina. Grocery store density and food waste. *Manufacturing & Service Operations Management*, 2020.

Arzum Akkas and Dorothee Honhon. Shipment policies for products with fixed shelf lives: Impact on profits and waste. *Available at SSRN 3247290*, 2020.

Qing Li, Peiwen Yu, and Xiaoli Wu. Shelf life extending packaging, inventory control and grocery retailing. *Production and Operations Management*, 26(7):1369–1382, 2017.

Baris Ata, Deishin Lee, and Erkut Sonmez. Dynamic staffing of volunteer gleaning operations. *Available at SSRN 2873250*, 2016.

Saed Alizamir, Foad Iravani, and Hamed Mamani. An analysis of price vs. revenue protection: Government subsidies in the agriculture industry. *Management Science*, 65(1):32–49, 2018.

Awi Federgruen, Upmanu Lall, and A Serdar Şimşek. Supply chain analysis of contract farming. *Manufacturing & Service Operations Management*, 21(2):361–378, 2019.

USDA Economic Research Services. Online, 2019. URL https://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-us/key-statistics-graphics.aspx.

Kimbery Morland, Steve Wing, and Ana Diex Roux. Supermarkets, other food stores, and obesity: the atherosclerosis risk in communities study. *Am J Prev Med*, 2006.

Nicole Darmon and Adam Drewnowski. Does social class predict diet quality? *The American journal of clinical nutrition*, 87(5):1107–1117, 2008.

Food and Nutrition Service USDA. Snap-ed budget allocations fy2017, 2017. URL https://snaped.fns.usda.gov/materials/fy-2017-final-snap-ed-budget-funding-allocations.

Adam Drewnowski. The cost of us foods as related to their nutritive value. *The American journal of clinical nutrition*, 92(5):1181–1188, 2010.

USDA ERS, 2017. URL https://www.ers.usda.gov/data-products/food-access-research-atlas/.

Alison Gustafson, James Allen, Nancy Schoenberg, and Mark Swanson. The relationship between neighborhood food environment and food store choice on purchasing habits among SNAP and lower income households, USDA FoodAPS data. In *University of Kentucky Center for Poverty Research Discussion Paper Series*. University of Kentucky, 2016.

Diansheng Dong and Biing-Hwang Lin. Fruit and vegetable consumption by low income americans: Would a price reduction make a difference? Economic Research Report 70, U.S. Department of Agriculture, Economic Research Service, 2009.

Cindy W Leung, Sarah Cluggish, Eduardo Villamor, Paul J Catalano, Walter C Willett, and Eric B Rimm. Few changes in food security and dietary intake from short-term participation in the supplemental nutrition assistance program among low-income massachusetts adults. *Journal of nutrition education and behavior*, 46(1):68–74, 2014.

Chantelle Bazerghi, Fiona H McKay, and Matthew Dunn. The role of food banks in addressing food insecurity: a systematic review. *Journal of community health*, 41(4):732–740, 2016.

Inge Spronk, Charina Kullen, Catriona Burdon, and Helen O'Connor. Relationship between nutrition knowledge and dietary intake. *British Journal of Nutrition*, 111(10):1713–1726, 2014.

The Reinvestment Fund. Online, 2019. URL https://www.reinvestment.com/initiatives/hffi/.

Hunt Allcott, Rebecca Diamond, Jean-Pierre Dubé, Jessie Handbury, Ilya Rahkovsky, and Molly Schnell. Food deserts and the causes of nutritional inequality. *The Quarterly Journal of Economics*, 134(4):1793–1844, 2019.

Michele Ver Ploeg and Ilya Rahkovsky. Recent evidence on the effects of food store access on food choice and diet quality. *USDA Economic Research Service*, 2016.

S Cummins, E Flint, and S A Matthews. New neighborhood grocery store increasing awareness of food access but did not alter dietary habits or obesity. *Health Affairs*, 33(2):283–291, 2014.

S Cummins, M Petticrew, C Higgings, A Findlay, and L Sparks. Large scale food retailing as an intervention for diet and health: quasi-experimental evaluation of a natural experiment. *J Epidemiol Community Healthy*, 59(1035-1040), 2005.

N Wrigley, D Warm, and B Margetts. Deprivation, diet, and food-retail access: findings from the Leeds 'food deserts' study. *Environmental and Planning A*, 35:151–181, 2003.

Meals on Wheels America. Online, 2021. URL https://www.mealsonwheelsamerica.org/learn-more/what-we-deliver.

Seth A Berkowitz, Linda M Delahanty, Jean Terranova, Barbara Steiner, Melanie P Ruazol, Roshni Singh, Naysha N Shahid, and Deborah J Wexler. Medically tailored meal delivery for diabetes patients with food insecurity: a randomized cross-over trial. *Journal of general internal medicine*, 34(3):396–404, 2019.

Ohad Eisenhandler and Michal Tzur. The humanitarian pickup and distribution problem. *Operations Research*, 67, 2019.

Hakan Yildiz, Michael P Johnson, and Stephen Roehrig. Planning for meals-on-wheels: algorithms and application. *Journal of the Operational Research Society*, 64(10):1540–1550, 2013.

Senay Solak, Christina Scherrer, and Ahmed Ghoniem. The stop-and-drop problem in nonprofit food distribution networks. *Annals of Operations Research*, 221(1):407–426, 2014.

Lauren B Davis, Irem Sengul, Julie S Ivy, Luther G Brock III, and Lastella Miles. Scheduling food bank collections and deliveries to ensure food safety and improve access. *Socio-Economic Planning Sciences*, 48(3):175–188, 2014.

Burcu Balcik, Seyed Iravani, and Karen Smilowitz. Multi-vehicle sequential resource allocation for a nonprofit distribution system. *IIE Transactions*, 46(12):1279–1297, 2014.

Vahideh Manshadi and Scott Rodilitz. Online policies for efficient volunteer crowdsourcing. In *Proceedings of the 21st ACM Conference on Economics and Computation*, pages 315–316, 2020.

Irene Lo, Vahideh Manshadi, Scott Rodilitz, and Ali Shameli. Commitment on volunteer crowdsourcing platforms: Implications for growth and engagement. *Available at SSRN 3802628*, 2021.

Robert W Lien, Seyed MR Iravani, and Karen R Smilowitz. Sequential resource allocation for nonprofit operations. *Operations Research*, 62(2):301–317, 2014.

Irem Sengul Orgut, Julie Ivy, Reha Uzsoy, and James R Wilson. Modeling for the equitable and effective distribution of donated food under capacity constraints. *IIE Transactions*, 48(3): 252–266, 2016.

Sefakor Fianu and Lauren B Davis. A markov decision process model for equitable distribution of supplies under uncertainty. *European Journal of Operational Research*, 264(3):1101–1115, 2018.

Retsef Levi, Elisabeth Paulson, and Georgia Perakis. Optimal interventions for increasing healthy food consumption among low income households. *Available at SSRN 3486292*, 2019.

Terry A Taylor and Wenqiang Xiao. Donor product-subsidies to increase consumption: Implications of consumer awareness and profit-maximizing intermediaries. *Production and Operations Management*, 2019.

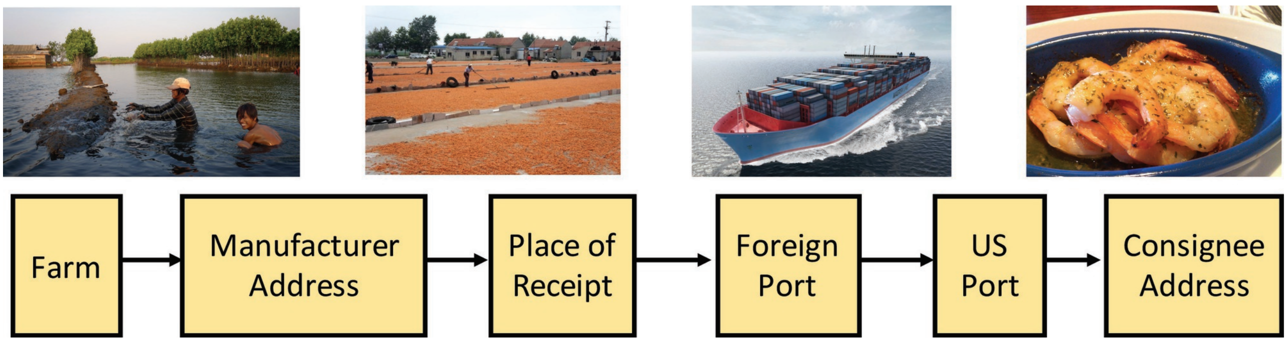
Retsef Levi, Georgia Perakis, and Gonzalo Romero. On the effectiveness of uniform subsidies in increasing market consumption. *Management Science*, 63(1):40–57, 2016.

Jiayi Joey Yu, Christopher S Tang, and Zuo-Jun Max Shen. Improving consumer welfare and manufacturer profit via government subsidy programs: Subsidizing consumers or manufacturers? *Manufacturing & Service Operations Management*, 20(4):752–766, 2018.

Saed Alizamir, Francis de Véricourt, and Peng Sun. Efficient feed-in-tariff policies for renewable energy technologies. *Operations Research*, 64(1):52–66, 2016.

Economic Research Service, USDA. FoodAPS National Household Food Acquisition and Purchase Survey . https://www.ers.usda.gov/data-products/foodaps-national-household-food-acquisition-and-purchase-survey/, 2020.

Vishal Gupta, Brian Rongqing Han, Song-Hee Kim, and Hyung Paek. Maximizing intervention effectiveness. *Management Science*, 2020.



nav_22020_sc_shipping.eps