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Big Data's Potential to Improve Food Supply Chain Environmental Sustainability and Food Safety

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Abstract

Big data is emerging as an important information technology to guide decisions within agri-food supply chains. Big data can be used potentially to differentiate and identify final products based on underlying farm production attributes demanded by consumers in the supply chain. This paper considers the challenges faced by the supply chain in responding to consumer demands and adoption of big data technologies in agricultural production through closer evaluation of two examples—one of which considers the use of a sustainability metric and the other considers the potential to increase food safety. We conclude with some comments about likely future issues and implications of the potential widespread adoption of big data.

Keywords: big data, supply chain, sustainability, food safety

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Introduction

Recently, in *A Framework for Assessing Effects of the Food System*, the National Research Council (2015) offered a general framework for assessing the entire food system. The framework moves beyond environmental sustainability, and considers the health, social and economic domains. However, this expansive framework is a long way from quantifying production practices that can be certified, as required to realize a consumer-driven supply chain. A scientific literature does exist on the development and validation of indicators of individual aspects of sustainability in selected farming systems, but these are generalized and not site-specific (e.g., see Bell and Morse 2008). Long term efforts have shown economic and environmental benefits of specific production practices facilitated by precision agriculture techniques. Similarly, the first point to keep pathogen contamination out of the food supply chain is in the production fields, where precision agriculture can facilitate monitoring and limit foodborne pathogens—especially important with fresh produce which receives minimal processing beyond the farm gate. However, on-farm practices are very site specific, and translating research into generalizations about safe and sustainable practices is problematic. Further, the remaining nodes in the food supply chain must be addressed in any system designed to increase the level of food safety.

Big data offers a technological breakthrough that may provide a means for translating "good" practices into generalizations that consumers can trust and be willing to pay for and, at the other end of the supply chain, firms could use for monitoring and evaluation of alternative solutions to providing sustainably produced and safe food. Even though consumers would be the ultimate beneficiaries, it is the intermediaries in the food supply chain who must identify and develop or adapt existing data sources needed to operationalize best practices. Developing means of successfully capturing the big data being created in the production process and analyzing it to create valuable tools and metrics for use by managers in production and supply chain firms requires new analytics adapted to the particular issues involved. In spite of the measurement challenges, there is growing interest on the part of major players in the supply chain to meet consumer expectations.[1] The challenges faced by food supply chain managers in responding to consumer demands are illustrated here through two examples: one considers the use of a sustainability metric and the other considers the potential to increase food safety. We conclude with some comments about likely future issues and responses of agri-food supply chain managers.

Evolution of Consumer Demand for Food Products

The business of farmers and food supply chains has traditionally been to provide consumers with food products that meet their marketplace demands for quality and affordability. Indeed, recent surveys indicate that consumers are most concerned with affordability, nutrition and food safety (Glassman 2015). There is also a long history, particularly in developed countries, of governments playing a role in encouraging (through incentives) and requiring (through regulations) agri-food supply chains to meet certain standards in their production processes. One justification for government involvement in the marketplace is the public good aspects associated with the production of the final products demanded by consumers. For example, the government has a shared responsibility to minimize foodborne

[1]For example, food chains make efforts to be listed as part of the Global 100—of the world's most sustainable corporations—announced annually at the World Economic Forum. Among the 100, four food companies were listed most recently: General Mills, Unilever, Coca-Cola, and Campbell's Soup.

disease outbreaks and environmental degradation. In both cases individual firms, particularly in the short run, have limited financial incentive to pursue them.

As evidenced by the contemporary foods movement (e.g., Pollan 2006), fueled at least in part by information technology (Streeter, Sonka, Hudson 1991; Poppe et al. 2013), consumers are paying closer attention to the products and processes of the food supply chains. For example, consumers are educating themselves about the dangers of foodborne diseases, as evidenced by an increase in internet searches following government reports of outbreaks (Kuchler 2015). In addition, consumers are widening their interests in the public good aspects of the food production systems, including environmental impacts of alternative production processes. Perhaps in response to the lack of government involvement in the food system or to preempt government involvement, food supply chains are increasingly becoming engaged in the provision of what heretofore have been considered public goods. At least in some part, firms are also pursuing the effort for marketing purposes (Elder and Dauvergne 2015).

The attributes that define a food product have recently expanded. For example, consumers are now offered a variety of egg products differentiated by the labeling of the on-farm production processes, such as produced by cage-free and free-range hens. However, this has also raised a concern that, especially as industry concentration increases, consumer choice may be restricted as a result of corporate decisions to limit the offering of products that respond to the demands of only a subset of consumers. Recent corporate decisions on the part of retail and fast food chains regarding cage-free eggs is an example. A recent article by Saitone, Sexton, and Sumner (2015) considers just such a case when a market response to consumer interests in food production processes can have the effect of limiting consumer choice and increasing costs. This occurs when players in the supply chain offer only selected food items produced using specified processes instead of offering a selection of products with alternative bundles of characteristics. In their study of antibiotic-free pork production, using simulations, they conclude that the increase in production costs led to significant reductions of both consumer and producer surplus. It is worth noting that the study focused only on private returns and not the public good aspects of the development of increased antibiotic resistance due to the use of antibiotics in pork production.[2]

The Corporate Awakening

As a more connected and informed consumer base has evolved, so too have agri-food supply chains in response to that evolution. Food supply chains can respond in a variety of ways to a more interested consumer population. Developing a positive reputation among the consumer base—so-called self-regulating—is important as a defensive strategy to possibly avoid costly government regulation or agency costs, i.e., costly lawsuits. It is recognized in the business management literature that firms are interested in demonstrating to their customers, through claims of Corporate Social Responsibility (CSR) that they care about the social welfare and environmental impacts of their businesses (Stephen 2004). In short, CSR involves spending more doing business than is required by law and regulation to accomplish a public goal (McWilliams and Siegel 2001; Paul and Siegel 2006).

Corporate managers generally have control over their firm's discretionary spending to exhibit CSR and the actions take many forms, from supporting local social causes near their headquarters to engaging in social or environmental activities generally related to their

[2] For a review of the evidence on these effects, see Teillent and Laxminarayan 2015.

industries. Firms may convey their responsiveness through general declarations of corporate social responsibility (CSR) which are not unlike the more traditional philanthropic donations (Hay, Stavens, and Vieter 2005). Major food companies have stated their intention to be more socially responsive by how they manage their businesses. For example, in the buildup to the United Nations Climate Change Conference meeting in Paris, November 2015, major agri-food companies were fully engaged in declaring their support of reducing greenhouse gases. This includes Cargill, PepsiCo, Wal-Mart, General Mills, Hershey, Kellogg's, Mars, McDonald's, Monsanto, ethanol firms Abengoa and Poet, and Campos Brothers Farms (Basher 2015). Another example of CSR from the food supply chain is Wal-Mart's goal to increase local foods sales—in some areas sourced from limited resource farmers—even though it is not established that local foods are superior nutritionally or lead to less environmental degradation.

There is not strong scientific evidence about the relationship between CSR claims and sustainability accomplishments and, in fact, there is some evidence that CSR claims are not improving food security and sustainability in developing countries (Elder and Dauvergne 2015). Similarly, there is little empirical evidence on how CSR claims affect consumer demand for food items. Moreover, given that agricultural supply chains are generally global in nature, the response of consumers to claims of CSR are expected to vary significantly.[3] While actions of CSR may buy the food industry good will, it may not be sufficient to meet consumer demands focused on the food products they purchase for attributes relating to food safety and claims regarding the underlying sustainable farm production processes. An entire industry has grown up regarding these claims and audits associated with verifying those claims. It is the potential availability of large data sets that may allow these claims to be made and verified, particularly in a commodity industry.

Reassurances to meet these more specific demands are only possible when there is an established scientific basis and a system designed to capture production information from the farm to the food product. The collection of location specific, auditable information represented by big data is poised to play a major role in that development. However, a potential danger to innovation in the supply chain could result from food processers pushing to become more consumer-driven. This would be the case if it leads to an excess of centrally-defined production paths to accomplish goals, which thereby crowd out historical farm-level innovation.

Big Data in Context

The term *big data* is used in a variety of contexts, inside and outside of agriculture, and is very broadly described. No satisfactory general definition exists. As noted in a recent National Research Council report on the topic, no satisfactory definition can be provided until there are general laws established that are scale neutral in their applicability (Committee on the Analysis of Massive Data, 2013). Descriptions of big data in the agricultural context generally emphasize extremely large data sets (generally built by integrating multiple sources of related data), analyzed with state-of-the-art computing power to reveal patterns, trends, and associations of value for a variety of decision making purposes. Our emphasis in this paper is

[3] For example, in an analysis of the impact of CSR claims on wine sales internationally, Muellor-Loose and Remaud (2013) found significantly different impacts across 5 developed countries. They also found that claims of CSR were valued less by consumers than the organic label.

in the use of large amounts of data integrated by those in the agri-food supply chain to provide consumers products with desirable attributes.

On-farm data collection related to detailed production practices, input use, disease outbreaks, food safety concerns, and yields has been occurring through the use of increasingly sophisticated machinery and equipment, often termed precision agriculture. Additional crops will benefit from these technologies as researchers work with industry to develop systems for particular crops. For example, the grape industry expects to benefit from precision vineyard management being developed under a current U. S. Department of Agriculture (USDA) National Institute of Food and Agriculture (NIFA) Specialty Crop Research Initiative grant. By collecting and analyzing thousands of images per minute, farmers will be able to hone their management practices to improve quality and quantity of their crops (Enos 2015). This should facilitate monitoring for pathogens or field conditions particularly susceptible to creating potential food safety risks, and taking remedial action or even removing suspect product from the supply chain at the farm level. Operators using this equipment and the sensor-based information generated have the potential to tailor seed variety, crop nutrients and other production practices down to a resolution of a few feet. This may help to improve profitability as well as reduce the operator's environmental footprint. It may also provide the input needed to evaluate sustainability metrics many companies are turning to in order to provide objective, measurable evidence of improvements in the environmental performance of a company's supply source.

The unique contribution of big data is to combine the vast amount of data from public investments, such as weather and climate predictions of major models, with aggregations of on-farm input and output relationships from relevant regions to develop alternative management strategies for desired outcomes. Industries associated with agriculture are finding creative ways to add value to these aggregated data, including selling management services to producers and monitoring the practices of their upstream producers to be used in the marketing of their products with specified attributes in their supply chain. However, there are still significant legal issues to be resolved because the current laws addressing intellectual property do not provide a clear interpretation for agricultural data as it relates to trademark, patent, or copyright law (Ferrell 2015). Farmers also have expressed concern about giving up the property rights to their own data (Thatcher 2015). In response to this concern, one tool was developed by a coalition of farm, commodity, and agricultural technology providers—The Ag Data Transparency Evaluator—to help producers understand where their data is going and who has access and control over it. Adequately addressing the legal issues, however, may require congressional action to revise the Uniform Trade Secret Act to encompass the uniqueness of agricultural data. Some farmers have pursued concerted action that can make their individual data valuable to them in assuring sustainable production practices and monitoring food safety practices at the local level. One strategy is banding together in cooperatives to aggregate and analyze their data, working with universities to develop analytic platforms. They can then protect the privacy of their individual data while sharing the added value within the cooperative membership. Such private sector actions, collaboration between farmers and providers of digital information systems, and/or public policy will need to sort out the privacy and legal issues involved.

The most recent development to help farmers manage their data and capture the value to them in documenting characteristics of their operation—which could include sustainability and food safety related metrics—is the formation of an Agricultural Data Coalition (ADC 2016). It is "focused on designing, creating and managing a central repository where farmers can store their information and oversee how it is accessed”. This will potentially allow farmers to maximize the value of their data by using it to accomplish their own goals. At the same time, it addresses some of the ethical issues of control and use of big data at the farm level end of the food supply chain.

Two Examples of Consumer-Driven Supply Chain Responses

While the primary motivation for a farmer to adopt the use of precision agriculture or big data is profitability, agri-food supply chains are poised to capture the information from production systems to make attribution claims of value to their customers. We consider two distinct industry responses: The first is industry responding to consumer demands for more environmentally sustainable grain production and the second involves industry responding to both consumer demands and federal regulation regarding food safety practices. It is interesting to note the differences between the two responses in the level of scientific knowledge of the outcome to be avoided, i.e., environmental degradation and negative health outcomes and even death due to pathogen risks in food. For food safety, when a significant outbreak resulting in deaths or illnesses occurs, the Centers for Disease Control makes an effort to identify the source of the outbreak and the federal government and industry respond. However, the system is in the process of changing since the final rules under the 2011 Food and Drug Administration's (FDA) Food Safety Modernization Act (FSMA) became effective in January 2016. The FSMA turns the primary focus to prevention rather than reacting to correct foodborne illness incidents and deaths and reduce costly recalls (FDA 2011). In contrast, it is more difficult to identify and measure an acceptable level of environmental degradation. Moreover, in contrast to a response to food safety concerns, solutions to environmental issues are less clear because it is difficult to identify simple trade-offs among on-farm production practices. The environmental situation is a classic example of what has been characterized as a "wicked problem" in agriculture (Batie 2008).[4]

The Maturation of the Sustainability Concept

The general and evolving concept of sustainability does not lend itself to simple measurement. The 1987 United Nations Report of the World Commission on Environment and Development, gave a definition of sustainability as “… implies meeting the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations 1987). In the report, three interrelated features were noted: economic viability, social equity, and environmental protection. The National Research Council in its 2010 report, *Toward Sustainable Agricultural Systems in the 21st Century*, proffered that sustainability meets four goals: (1) To satisfy human food, feed, and fiber needs, and contribute to biofuel needs. (2) To enhance environmental quality and the resource base. (3) To sustain the economic viability of agriculture. (4) To enhance the quality of life for farmers, farm workers, and society as a whole. Sustainability is the greatest, the report also hypothesized, when a generalized set of production processes has the greatest overlap of these goals. Implementation of the environmental goals of sustainability is particularly challenging for agriculture because of the multitude of factors that are relevant in measuring the impact of

[4] An early literature on Post-Normal Sustainability Technologies is exploring how to frame wicked problems in public policy (Funtowitz and Ravetz 1990).

production practices. Improvement in one dimension of environmental performance, may come with environmental degradation in another (Aigner, Hopkins, and Johansson 2003).[5]

The quest for sustainability has become a focus for consumers. It has also become a driver of innovation in the agri-food supply chain. In a recent Harvard Business Review article, sustainability is seen as driving innovation to meet new regulatory standards and create value chains in cooperation with downstream and upstream partners (Nidumolu, Prahalad, and Rangaswami 2009). As the concept of sustainability has matured, the agri-food supply chain is at the initial stages of utilizing the tools of big data to more efficiently evaluate farmers' actions in reducing their environmental footprint. These evaluation systems can take considerable time. For example, the "Field to Market" sustainability calculator takes as much as thirty minutes to populate the model for one field. That information provides measures of soil erosion, energy and water use and crop nutrient efficiency among others. To as great an extent possible, the calculator pre-populates many of the required data inputs such as soil type or field slope by linking to federal data sources, but the production practice information still requires the farmer to spend input time. To provide that information for the entire farm may well take hours. Linking information directly from the farm's machinery compliment will one day hopefully negate the need for this kind of time commitment as well as providing for a much more detailed look at the farm's environmental performance. It may also allow the farmer to self-develop best management practices for the operation using the farm data itself as a set of replicated experiments. From a CSR perspective, the company purchasing the farm's product would have access to detailed environmental measures as well as data backing up any continuous improvement claims.

While sustainability purports to embrace goals of economic profitability, natural resource conservation, and quality of life, in practice, quality of life goals are often ignored in developed countries. In developing countries, agricultural development and rural development are more closely linked since rural livelihoods and agricultural profitability are often one and the same, but they often rank low on quality of life indicators. The balancing of the triple bottom-line of sustainability—economic, environmental, and social—is very much a work-in-progress for agri-food supply chains which are global in nature. For example, Hidayat, Glasbergen and Offermans (2015) analyze the implications of sustainability certifications developed to meet the environmental goals of one regional market but where the production occurs in another region that experiences significant social impacts to rural livelihoods.

Sustainable Label in Grain Production

Translating sustainability into the marketplace for agri-food products is driving companies as well as farmers and ranchers to re-evaluate what have been traditionally viewed as good farming practices. It is also bringing into question policy approaches to environmental performance improvement efforts that have been in place for decades. One of the major contributions of big data will be to help companies and agriculture measure the sector's

[5] The International Organization for Standardization (ISO) is the world's largest developer of standards, currently with 162 member countries and standards dedicated to food production, sustainable development, water, and other areas of relevance to agricultural production. The Sustainable Agriculture Initiative (SAI) is an organization established by the food industry which supports sustainable agricultural practices. The challenges in implementing these types of certification of standards have been documented (e.g., by UNEP 2000) and sometimes criticized by consumer and environmental groups (e.g., Friends of the Earth).

performance, while also granting individual companies the data paths they feel are necessary to make sustainability claims.

The interface between CSR claims and commodity agriculture continues to create challenges for all involved. Companies want to be able to make claims regarding their individual activities toward their CSR goals. For identity preserved product, these claims are fairly easy to make and verify. With Price Lookup Code (PLU) stickers on individual pieces of fruit or vegetables along with coding on the box itself it is possible to trace a head of lettuce back to the row of the field from which it was harvested and in many cases even down to who was working on the crew that particular day. For products with PLU codes the entire claim and verification process is straightforward. Identity preservation claims for what are usually viewed as bulk commodities can be relatively expensive.

One of the most widely used class of products are organic grains and oilseeds. At the end of September 2015 the Agricultural Marketing Service of the USDA reported the national average price of organic corn at $10.74/bushel while at the same time corn was selling for $3.66 per bushel in Chicago. Simultaneously, organic soybean prices were reportedly at $21.81 per bushel while conventional beans were at $8.62 per bushel (USDA 2015). A twenty-five pound bag of tofu quality soybeans was available through Amazon for $68.88 plus shipping in early October 2015. Again, the organic designation has a large enough market share to have its own distribution, price discovery and marketing channels. For an individual company trying to establish their own supply chain for a given set of production practice requirements, the costs are quite large at nearly any kind of scale.

There are companies, however, with sufficient market share, to make demands that may require the entire chain to consider alterations in production practices. A 2013 Forbes article pegged Wal-Mart with a 25% share of national grocery sales (Leeb 2013). Wal-Mart also has a well-developed sustainability effort, requiring their suppliers to devote considerable effort to document their work toward reducing greenhouse gas emissions, water usage and other environmental measures (Wal-Mart 2015). Other consumer-facing companies such as Unilever have well established sustainability programs and are working on pilot programs to source sustainable soy in the United States, using Unilever’s sustainable Agricultural Code (Unilever 2015). But the pilot discussed in the Unilever case covered only 160,000 acres in 2014 according to this same website and 83 million acres were planted to soybeans in the United States in 2014. Unilever has stated a goal of having a million acres enrolled in a sustainability calculator, "Field to Market," by 2017. Data collection on a farm-by-farm basis through surveys is not without cost, which is exactly why many are looking to big data and automated data collection systems as the mechanism whereby the sector and the companies will be able to make sustainability claims.

Sustainability claims for many products require a producer to go through an extensive checklist, reporting on everything from nutrient use to labor practices. The Field to Market program discussed by Unilever—and looked to by many in the commodity crop space—utilizes a set of metrics that currently require significant input from the farmer to complete. These are then benchmarked against other data from the local area or a group of other selected producers who are usually participating in the same pilot program. Field to Market currently has more than eighty groups (grower organizations; agribusinesses; food, fiber, restaurant and retail companies; conservation groups; and universities) as partners (Field to Market 2015).

There is an effort underway to convert these same metrics so that they will interact directly with data management systems consistent with those maintained for giving cropping prescriptions. This big data approach means the data accuracy would reflect that collected straight from the piece of operating equipment and would significantly reduce the need to audit the data collected. If, or when, this can be taken through to execution it would allow the sector to make the same kind of sustainability claims over tens of millions of acres quickly as opposed to the few hundred thousand acres currently enrolled. However, computer scientists are only beginning to address the technical infrastructure challenges presented by big data analysis which will require hardware and software advances in both parallel and distributed processing systems. While additional observations and new data sets can improve the ability to address a problem and/or expand applications, their processing infrastructure also raises challenges due to heterogeneity in representations, data quality, and openness (Committee on the Analysis of Massive Data 2013, Chapter 4). Concerns about data ownership and confidentiality, in particular, have surfaced early in the development of big data technologies for agriculture. Computer technologies are needed which protect the privacy of confidential data from leakage and malicious harvesting, while fusing various data sets, through hardware parallelism.

Enhancing Food Safety in the Supply Chain

Food safety throughout the supply chain is an ongoing concern. Though much effort goes into assuring safe practices in food production and handling, a large number of foodborne illnesses and deaths are experienced annually within the United States. One estimate of the cost of foodborne illnesses is $56–$93 billion annually, based upon immediate treatment cost and lost income of individuals but not accounting for potentially significant costs related to long-term health impacts (Scharff 2015). Contamination may occur at any point in the food supply chain starting at the farm level, thus creating challenges in identifying the cause of foodborne illness outbreaks. Since there are many more instances of foodborne illness than are identified and traced to a source, the private market incentives to optimize food safety are somewhat weak across the entire food supply chain. A lack of information available to consumers, industry, and policy makers creates problems in preventing foodborne illness from pathogens, but there are several options to provide better information. These include more financial support of databases and research by federal agencies; a farm-to-table database to trace pathogens to specific farms, food companies, and products; creation of a national product liability database documenting court cases including out-of-court settlements for foodborne illness cases; and establishing a Cabinet level or independent consumer protection agency to foster collection of data on pathogens in the US food supply (Roberts 2013). However, there are significant incentives for preventing foodborne illness, especially for major branded retailers and food service establishments where the value of their brand and franchise could be greatly diminished or destroyed by a serious foodborne illness incident. For example, sales in established, i.e., open a year or more, Chipotle Mexican Grill, Inc. restaurants fell 30% in December 2015 from the previous year. Chipotle stock market value fell to as low as $400 per share from over $750, a 53% decline in implied company market value, following a series of E. coli and norovirus food safety incidents in its popular restaurants, starting in October 2015 (Jargon and Newman 2016).

One means of protecting their brand is for a company to incorporate a strong risk management strategy as a critical part of its business plan (Brackett 2015). Denmark has used a collaborative approach between government and industry to eliminate salmonellosis in the poultry supply chain, which had become a serious problem. According to the vice president for food safety at Cargill Turkey and Cooked Meats, they already find it in their best interest to control what goes on at the farm and any new regulatory requirements are not likely to much change what they are already doing (Clapp 2015). Given the critical nature of food safety to a company's brand and ability to participate in the supply chain for such brands, most food companies undoubtedly have a somewhat similar philosophy and practice. But the voluntary nature of the US food safety system and frequently a lack of access to data regarding safety in the supply chain means that challenges remain.

As mentioned, the current voluntary food safety system is about to change under the 2011 FDA Food Safety Modernization Act (FSMA), which is the first update to US food safety laws since 1938. It gives FDA more authority to regulate fresh produce and animal feed, food imports and transportation, and provide oversight of third-party auditors. Sec. 206 of the Act provides the FDA with authority to mandate recalls of contaminated food if the responsible party does not cease distribution or recall a product (FDA 2011). The final rule on preventive controls for human food under FSMA establishes key requirements and compliance dates by which "covered facilities must establish and implement a safety system that includes an analysis of hazards and risk-based preventive controls", documented in a written safety plan. The rule provides flexibility in oversight and management of preventive controls. This must include "monitoring ... appropriate to the preventive control", corrective actions for "a minor, isolated problem that occurs during food production", and verification "that preventive controls are consistently implemented and effective." It clarifies that Primary Production Farms and Secondary Activities Farms are not subject to the preventive controls unless they handle produce covered by the Produce Safety Rule with which they are required to comply. It also "mandates that a manufacturing/processing facility must have a risk-based supply chain program for those raw material and other ingredients for which it has identified as a hazard requiring a supply-chain applied control" program. The final rule also updates and clarifies Current Good Manufacturing Practices (CGMPs) (FDA 2015).

One approach to increase incentives and accountability for improved food safety is to identify good manufacturing practices for food processors and handlers at various stages in the food supply chain. There are examples of industry efforts to establish such initiatives within their sphere of influence, relying on voluntary compliance with guidelines developed by industry organizations. An example is guidelines which provide recommended food safety practices for the fresh tomato supply chain which are intended to minimize microbial hazards associated with fresh and fresh-cut tomato products. The North American Tomato Trade Work Group (NATTWG) and the United Fresh Produce Association provided leadership for this effort involving a number of associations, agencies, companies and individuals with expertise in food safety practices. The guidelines are divided into eight primary modules starting with open field production through food service and retail. Each module addresses key considerations to control potential sources of pathogen contamination reasonably likely to occur in the absence of such control. These guidelines are intended to enhance safe growing, processing, distribution and handling of the commodity from field to consumer, supplementing existing food safety programs encompassing Good Manufacturing Practices (GMPs) and Hazard Analysis Critical Control Point (HACCP) programs (Gombas et al. 2008). A proliferation of sensor technologies to gather big data are available for use throughout the food supply chain from farm to field to consumer point of purchase. With appropriate analytics to provide needed information, the data can facilitate management application of the guidelines to enhance food safety. Industry organizations could further incentivize compliance through educational efforts within the industry and publicizing the existence of the guidelines to consumers, simultaneously monitoring compliance and recognizing those firms formally adopting the guidelines.

A public sector approach would be to specify a set of required actions for food processors and handlers, which would then be monitored continuously at the various nodes in the supply chain. The monitoring could be a direct government function as in the case of a number of U.S. Department of Agriculture (USDA) programs related to food safety, product quality grades, and standards of product identity. Alternatively, the USDA could certify third-party organizations to carry out the ongoing monitoring, as is currently done to assure that food sold as organic is indeed produced in compliance with the National Organic Standards Act requirements. Making public the names of firms violating food safety requirements could incentivize compliance (National Research Council 2011), or a system of fines could be put in place for violation of requirements. This kind of continuous monitoring—by either the private or public sector—would produce prodigious amounts of data from which innovative analytics would be required to sort out useful information, i.e., a big data solution. The advantage would be the possibility of heading off potentially calamitous foodborne illness events that could affect from only a few to thousands of consumers with various degrees of illness severity, avoiding long term health impacts, and mitigating significant private and public cost consequences.

Either of the above approaches would require prioritizing interventions to control pathogens. Risk assessment and cost benefit analysis can be used to evaluate pathogen interventions in the food supply chain and provide a basis for such prioritization. This could provide a basis for increasing information available to consumers as well as businesses throughout the supply chain. The most stringent approach would establish databases tying specific foodborne illnesses to particular food producers, products or companies (Roberts 2015).

As pointed out earlier, the initial place to keep pathogen contamination out of the food supply chain is in the production fields, particularly with fresh produce which receives minimal processing beyond that point. An effort to create a GIS-based online tool to identify specific points in a field where foodborne pathogens are prevalent can provide growers a risk-based strategic approach to focus food safety attention. Heat maps pinpointing relative levels of risk in each field would reduce the difficulty of successfully adopting this approach at the farm level to keep potential pathogens from entering the food supply chain (Wiedmann 2014). A Cornell university project funded by the Center for Produce Safety is working to create a modeling tool which is GIS-based to identify specific locations within fields where risk of pathogen contamination may be higher. The GIS tool will utilize unique characteristics of a farm including soil moisture and precipitation, two big data driven elements, to identify areas of the farm they should target to employ science-based strategies to mitigate risk of contamination. Another Center for Produce Safety project will develop an application for computer or cell phone use to allow producers to minimize the illness outbreaks from E. coli and salmonella contamination from irrigation water, a frequent source of foodborne illness in fresh produce. A model will help growers determine the need for increased risk-based sampling based on rainfall, irrigation methods and type of produce. Utilizing local weather information will make this approach usable in many different areas of the country to determine needed frequency of sampling following rainfall which is a significant influence on surface water quality (Rock 2014).

At the industry level, public and private sector networks to analyze the data tracing food safety outbreak causes exist within countries and in international contexts. The 2011 FDA

Food Safety Modernization Act created incentives for the US private sector to adopt HACCP practices which include properly cleaning processing plants and keeping foods properly refrigerated during transport. Low cost but accurate sensors for continuous monitoring allow companies to strengthen food safety.

Scanning equipment in plants, ubiquitous personal devices, shipment tracking, and retail monitoring of consumer purchases creates the big data with potential to enhance traceability throughout the supply chain (Armbruster and MacDonell 2014). The potential to trace specific lots of food from a particular node in the supply chain to a specific location on the retail shelf or food service establishment receiving food identified as potentially contaminated is within reach. This could greatly reduce the costs of recalls relative to a complete removal of all product produced by a firm during a given time period. Speeding up the recall and making it more focused could increase the chances of removing the food before consumption rather than notifying the public after much or at least some amount of the potentially contaminated food has been consumed.

The rapid growth in demand for animal-based foods and vegetables—both rather risky for food safety—in rapidly emerging economies is a particular concern for preventing foodborne illnesses. Further, intensification of agriculture to meet this growing demand in countries where governments systems strain to keep up with rapid growth is of particular concern. Given that food safety and prevention of foodborne illnesses are global public goods, international cooperation and investment to ensure safer foods will be needed both by international organizations and national governments (Grace and McDermott 2015). The FSMA contains more rigorous food safety requirements for US imports. The implementation and enforcement of those provisions will determine the extent to which it adequately protects consumers from unsafe food imports over time.

Key to utilizing big data to improve food safety is much faster pinpointing of foodborne illness outbreak causes and sources; relevant technologies are being developed throughout universities and the private sector. For example, a particularly promising technology is a machine using optical scanning, laser sensor technology developed by Purdue University. It is capable of pinpointing eight specific strains of salmonella as well as identifying a number of the other most important foodborne illness pathogens with an accuracy greater than 95%. Its big advantage is the ability to produce results within twenty-four hours, as opposed to the current industry-standard of seventy-two hours. It has the potential to provide an inexpensive, efficient preliminary screening tool, an appealing prospect for the food processing sector which should lead to rapid adoption of this technology once it is perfected for use (van Hoose 2015). The implementation of this optical scanning, laser sensor technology could be very valuable in preventing potential foodborne illness incidents through screening processing/ handling/transportation operations in the supply chain where monitoring would produce voluminous data points to allow pinpointing a problem. Appropriate analytics would be required to process the data for real time decisions, and allow connecting any problems with earlier points in the supply chain which may contribute to them. By preventing potential incidents of food borne illness, the consumer would be directly impacted by avoided health impacts and related costs. The firms implementing such a system would need to publicize the extent to which they were going to prevent food borne illness, since the process would not be apparent or observable by consumers.

Concluding Comments

Consumers increasingly want to purchase food produced with certain underlying farm production practices, while having confidence in the safety of the food. The food industry increasingly wants to provide consumers with reassurances about these characteristics, while maintaining the efficiencies for which the industry is known. Farmers, too, want to continue to earn their reputation as good stewards of the land producing high-quality, safe, and affordable food at profitable levels. However, there are a number of barriers to the implementation of these goals in the supply chain. This paper has addressed the potential for the use of big data to help overcome some of those barriers and improve the performance of supply chains in meeting consumer demands.

Returns from scientific investments, good practices, field-level precision agricultural techniques and, of course, the underlying technology boom in general, have allowed for the emergence of the possibility of using big data to improve the efficiencies of the agri-food supply chain. A barrier to marketing products as nutritious, safe, and sustainably produced is that the science is not clear. In addition, consumers are sometimes saddled with misinformation. While there will always be a lag from knowledge generated in the scientific lab to adoption in the supply chain, big data can help to reduce that diffusion time and strengthen confidence in the results. We highlighted two examples of emerging supply chain responses to consumer demands for attributes associated with production processes and the quality and safety of the final product. To date, science-based regulation has played a larger role in providing incentives to supply chains regarding food safety objectives, compared to environmental sustainability objectives. In contrast, the linking of environmental attributes to food products has largely been initiated within the supply chain in response to consumer demands, either through the certification of attributes which are priced into the final food product or as part of a company's Corporate Social Responsibility agenda. As governments around the globe begin to respond to climate change outcomes in the form of international agreements to reduce carbon emissions, the supply chains could see more incentives provided by government regulation. Although the two examples highlight different roles for government as a result of the underlying scientific challenges, big data is poised to play an even greater role in the efficiency of the supply chains.

There are often unintended consequences of any technology adoption. In the adoption of big data as a tool in organizing and managing agri-food supply chains, we have mentioned three. First, big data in concentrated global supply chains may lead to a loss of consumer options, the hallmark of thriving markets. This is especially true in the case of products with environmental sustainability attributes, since most consumers are less willing to incur the private risks associated with foodborne illnesses than they are the less certain risks associated with long-term environmental degradation. Secondly, if not managed appropriately, there is a danger that the traditional source of innovation from individual farm-level management strategies will be lost to the supply chain through over prescription of farm practices. Finally, the adoption of big data technology on the farm may not be scale neutral (or spatially-neutral). Part of the stated triple bottom-line of sustainability is the focus on social equity, oftentimes interpreted to mean a farming system without extreme production concentration. Adoption of big data technologies is likely to accelerate the concentration in production agriculture.

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