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A system dynamics approach for examining mechanisms and pathways of food supply vulnerability

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Abstract

Understanding vulnerabilities in complex and interdependent modern food systems requires a whole-system perspective. This paper demonstrates how one systems approach, system dynamics, can help conceptualize the mechanisms and pathways by which food systems can be affected by disturbances. We describe the process of creating stock-and-flow maps and causal loop diagrams from the graphical representation of a problem and illustrate their use for making links and feedback among the human health, food, and environmental health sectors visible. These mapping tools help structure thinking about where and how particular systems might be affected by different disturbances and how flows of material and information transmit the effects of disturbances throughout the system. The visual representations as well as the process of creating them can serve different purposes for different stakeholders: developing research questions, identifying policy leverage points, or building collaboration among people in different parts of the system. They can serve as a transition between mental models and formal simulation models, but they also stand on their own to support diagrammatic reasoning: clarifying assumptions, structuring a problem space, or identifying unexpected implications of an unplanned disturbance or an intentional policy intervention. The diagrams included here show that vulnerability of a national food system does not only or automatically result from exogenous shocks that might affect a country. Rather, vulnerability can be either intensified or reduced by the interaction of feedback loops in the food system, and buffered or amplified by the structure of stocks and flows.

Keywords

Causal loop diagram; conceptual models; dynamic complexity; modern industrialized food systems; stock-and-flow diagram; systems mapping, structural insights.

Introduction

Food supply systems are richly integrated and highly dynamic social—ecological systems in which ecological factors shape the possibilities for food production and social factors govern the goals and operations of actors in the system. In low income countries, food supply systems tend to be relatively simple and closely adapted to local environmental conditions, with a small set of products and few steps between producers and consumers. Consumers are likely to participate in the system and understand how it works. By contrast, the structure and operation of modern industrialized food systems are largely invisible to consumers and policy-makers (Reisch et al. 2013). The chains of production, processing, and distribution activities that generate food supplies are long, highly differentiated, and influenced by an array of environmental, economic, social, cultural and other factors. It is hard to visualize connections in the system and even harder to see how changes in one part of the system affect other parts. Some causal connections in the system are direct and obvious, such as the effect of a drought on crop yield, but some are indirect and opaque, such as the effect of changing consumer preferences on what kinds of crops are grown. Feedback connections between sectors make effects of changes in one part of the system on another difficult to anticipate (Ericksen et al. 2010a). Food supply is both a food system outcome and an input to other food system outcomes such as human health. Human health can further affect labor availability and productivity, which feeds back to affect food supply through all the steps in the food chain. Food production is also tightly coupled with environmental health. Farming practices affect soil fertility, for example, which determines the need for external inputs such as fertilizers. These system-level feedback mechanisms increase the distance, both geographically and institutionally, between food system activities and impede the flow of information in the food system. It thus becomes more and more difficult for food system stakeholders to make informed decisions about management and consumption and to trace disturbances in a food system through to their effects (Sundkvist et al. 2005). As food systems become more complex, it becomes increasingly difficult to see where the system might be vulnerable to disturbances that would disrupt food supply or how major disturbances would propagate through the system.

In this paper, we use system dynamics concepts and diagramming tools to address Marten's (2015, this issue:**PAGE**) framing questions about food system vulnerability in the kinds of modern industrialized food systems found in high income countries such as the U.S. Defining food system resilience as *the ability of the food system to withstand disturbances that could lead to disruption of the food supply*, he asked: What are the main lines of vulnerability in the food system? What are leverage points for reducing the risks and improving the capacity to deal with breakdowns if they occur?

System dynamics is an approach for examining how things change over time. The central principle of system dynamics is that a system's internal structure—the cause-and-effect connections among system components—determines the dynamic behavior of the system and how it responds to disturbances (e.g., Sterman 2000). A household heating system, for example, might include a furnace, ducts to transfer hot air from the source to various rooms, a thermostat to sense the temperature and send a signal to turn on the furnace, and occupants of the house who set the desired temperature of the thermostat. The fluctuation of temperature in the house is one measure of the system's behavior. When the heating system is subjected to a sudden change in temperature, loss of power to the thermostat, or lack of fuel in the furnace, temperature in the house responds according to the particular structure of the system. Similarly, food supply fluctuates in response to disturbance based on the structure of the food system. Thus, any examination of food supply vulnerability to disturbance, or ability to withstand disturbances that could lead to food supply disruption, should start by examining the food system's components, causal connections and feedback mechanisms and describing system interactions in terms of material and information flows that pass changes in one component on to other components.

System dynamics is often used to create a computer simulation model for testing the response of a particular system to unforeseen shocks and deliberate policy interventions. Using a simulation model helps develop *dynamic insights*, that is, an understanding of reasons for and ways to change a system's problematic behavior. However, system dynamics can also be used to promote *structural insights* about the relationships among components in the system. For this purpose, the use of diagramming tools to create system maps is central.

Here we focus on the use of system dynamics to promote structural insights. We show how system dynamics concepts and diagramming tools can (1) visually represent the causal structure of food systems, (2) identify points of entry for disturbances external to the system, and (3) map the pathways and mechanisms that transmit, and amplify or absorb the effects of those disturbances. Two types of visual representations—causal loop diagrams and stock-and-flow diagrams—are used in system dynamics to capture the structure of a complex dynamic system (Sterman 2000). Causal loop diagrams consist of variables connected by arrows denoting the causal influences among the variables and the feedback loops, chains of causal links that close or feed back on themselves, in the system. Stock-and-flow diagrams highlight the accumulations (stocks) in a system and the processes that increase or decrease the stocks (flows). These types of diagrams, or system maps, formalize connections among system components. They make it easier to see where different triggers might affect a particular system and how flows of material and information convey the effects of disturbances throughout the system. Causal loop and stock-and-flow diagrams are used extensively in system dynamics to conceptualize the structure of the system (Lane 2008). While they often serve as a transition between mental models and formal simulation models, they also stand on their own to support what Hoffman (2011) describes as diagrammatic reasoning: clarifying assumptions, structuring a problem space, or identifying unexpected implications of an unplanned disturbance or intentional policy intervention (Hoffman 2011; Giardino 2013). Testing the system's response to different kinds and magnitudes of disturbance would require a fully operational simulation model, which is beyond the scope of this paper.

Our primary objective is to explain and demonstrate the system dynamics approach for examining food systems closely, rather than conduct a comprehensive examination of vulnerabilities. We draw on literature about food system vulnerabilities for the analysis, and frame the problem that guides the analysis very broadly. The analysis is most useful for those not already familiar with the system dynamics approach or the use of system dynamics or other systems approaches to create simulation models.

The remainder of the paper is organized as follows: after a brief overview of the system dynamics model building and analysis approach, we apply the first two steps of the approach, problem definition and system conceptualization, to food systems. We present three system maps representing different aspects of system structure. The first is a high-level sector map, derived from a specific concern about potential food supply disruption. It identifies two sources of potential instability inherent in the system structure, and shows the separation of the human sector from the environmental sector. The second diagram is a stock-and-flow representation expanded from one stock in the sector map. It illustrates the flow of food through various stages in the food supply chain. This diagram shows where exogenous sources of vulnerability affect the system. It also identifies endogenous sources of vulnerability that are caused by the dynamic feedback processes governing supply chains. The third diagram describes causal relationships and feedback mechanisms that affect food production. This diagram shows reinforcing loops that push producers to continually increase yields at the expense of natural resource health. This compromises diversity and thus adaptive capacity.

Modern Industrialized Food Supply Systems

Food systems in high income countries seem remarkably stable. Even when exposed to extreme weather events (e.g., Lengnick 2014), sudden changes in food and fuel prices (e.g., Misselhorn et al. 2010; Liverman and Kapadia 2010), transportation labor protests (e.g., PSEPC 2005), and other shocks, they often recover relatively quickly and continue to provide essentially the same food outcomes for consumers. However, some characteristics of contemporary food systems, as well as concerns about global environmental change, population growth, and urbanization, raise questions about the extent to which they could absorb such disturbances, and what triggers might activate tipping points beyond which the system could not adjust.

Food system disturbances are often discussed as shocks or stressors (Adger 2006; Leichenko and O'Brien 2008). A food system shock is a major, but generally short-term disturbance to the system. Examples of shocks include weather events such as droughts, floods, or storms; energy shocks such as power grid brown- or blackouts, or fuel shortages; or labor-related crises such as disease pandemics. A stressor is a longer-term but potentially more moderate disturbance such as climate change, cost increases for agricultural inputs, or health-related changes that might reduce labor productivity. System disturbances can also be institutional or policy-related.

Sundkvist et al. (2005) argue that intensification, specialization, and homogenization of food production, and greater distances between production and consumers increase food system vulnerability especially in high income countries because these processes increase the difficulty of the food system to adjust to changes in preferences, ecological or economic drivers. The size and complexity of food systems in industrialized countries also makes it difficult to see threats to the system as a whole, and leads to a focus on specific issues such as obesity and malnutrition rather than on mechanisms generating food and nutrition insecurity (Hammond and Dubé 2012). Other specific concerns include greenhouse gas emissions from the food chain (Garnett 2011), the environmental health of the movement toward local food sources (Edwards-Jones 2010), the effect of convenience stores on food choices (Sharkey et al. 2013), and the effect of consumption patterns on land use requirements (Gerbens-Leenes and Nonhebel 2002). The many stakeholders in the system, including policy-makers, producers, processors, retailers, civil society organizations and consumers, all bring their own views and values to food system issues and have different perceptions of the food system itself (Sadler et al. 2014). Consumers in particular tend to view the food system through their "lived experience" (FrameWorks Institute 2006a,b). Since fewer consumers in high income countries are engaged in food production than in low income countries, they are likely to experience the food system only through grocery shelves well stocked with processed food products. The source of the food and its journey to their plates is largely invisible, as are potential disruptions to food availability. Reisch et al. (2013) note that seasonality of production is irrelevant for consumers in industrialized countries because globalization ensures that fruits and vegetables are available throughout the year at relatively low prices. This consumer estrangement from food production and focus on "lived experience" with food makes it difficult to engage the public in constructive dialogue about systemic food issues (FrameWorks Institute 2005)

Understanding how food supplies might be vulnerable, especially in these large, diverse, multi-stakeholder systems, requires a broad perspective to examine the ways the food system as a whole is vulnerable (Eakin 2010; Ericksen 2008). IPCC (2001) and Ericksen et al. (2010b) describe the vulnerability of any food system as a function of its exposure to short-term shocks and longer-term stressors, sensitivity to those disturbances, and capacity as a whole to adapt. Exposure is the degree to which a food system is subjected to a particular disturbance. A coastal region food system might have a high degree of exposure to periodic flooding, for instance, while an inland system may have a low exposure to flooding. Sensitivity refers to the effect a given disturbance would have on the system. An extended drought may be devastating to a temperate-region food system but tolerated to a greater extent in an arid-region system because of different seed varieties, cropping systems, or irrigation technology. Adaptive capacity is the ability of the system to adjust to the effect of a disturbance and still continue to perform the same functions. A system that produces diverse sources of protein, for example, could still provide adequate nutrition in the face of a disease that decimated livestock by shifting more resources to producing other kinds of protein. A system with more limited products would have less ability to adapt to a similar shock. Applying this context of vulnerability to a given system raises questions about which short-term shocks and longer-term stressors the system is expected to be exposed to and to what extent, the expected response of the system to those disturbances, and how the system might compensate for the effects of such disturbances.

Food system representations

A number of high-level systems frameworks provide a starting point for examining food system vulnerability. Figures 1a, 1b, and 1c show three such conceptual models. Figure 1a sets food system vulnerability in the context of environmental and societal change. It gives little detail about food system structure but connects two major sectors to food system vulnerability through two different pathways. It represents vulnerability to environmental change as a function of exposure to an environmental hazard and capacity of the system to cope with change, which is also a function of social factors and institutions. It proposes that food system vulnerability then feeds back into environmental and societal change, a fundamental feedback mechanism that would govern the system's ongoing adjustment to change. This diagram raises questions about the ways a particular food system might be exposed to environmental change, how that exposure might be mediated by societal change, how environmental and societal factors might affect the system's capacity to cope with environmental shocks or stressors, and in what ways vulnerability leads to further environmental and societal change.

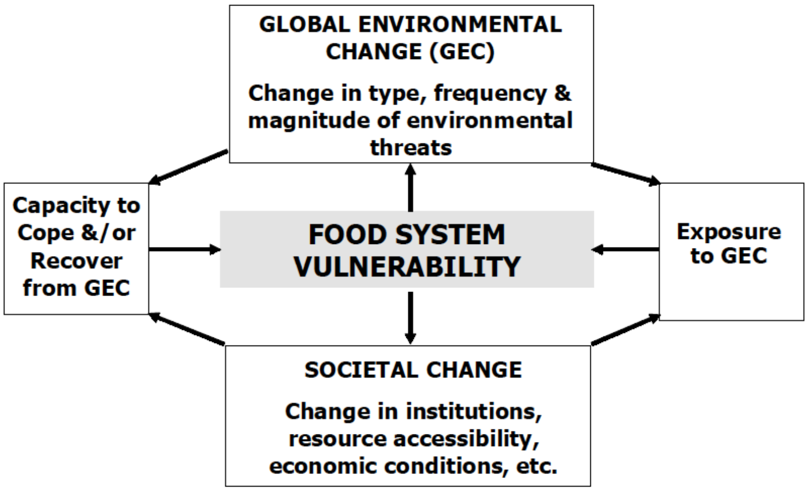

Figure 1a: Human vulnerability in the context of global environmental and societal changes (Ingram and Brklacich 2002: 431)

Figure 1b presents more detail about food system components, showing connections between environmental, farming, economic and social sectors across fuzzy boundaries. It shows the major subsystems and the key connections among them underlying demand and supply. Inputs are combined in processes and mediated by other system influences to generate food supply and demand. It reminds us to acknowledge people in the system. This diagram does not differentiate among different types of connections. The arrows in the diagram represent a variety of things, including flows of material, more general influence relationships, sequential steps in processes, and points along different levels of scale. This diagram gives a broad overview of how to describe a food system and leads to questions about how a particular food system might be structured.

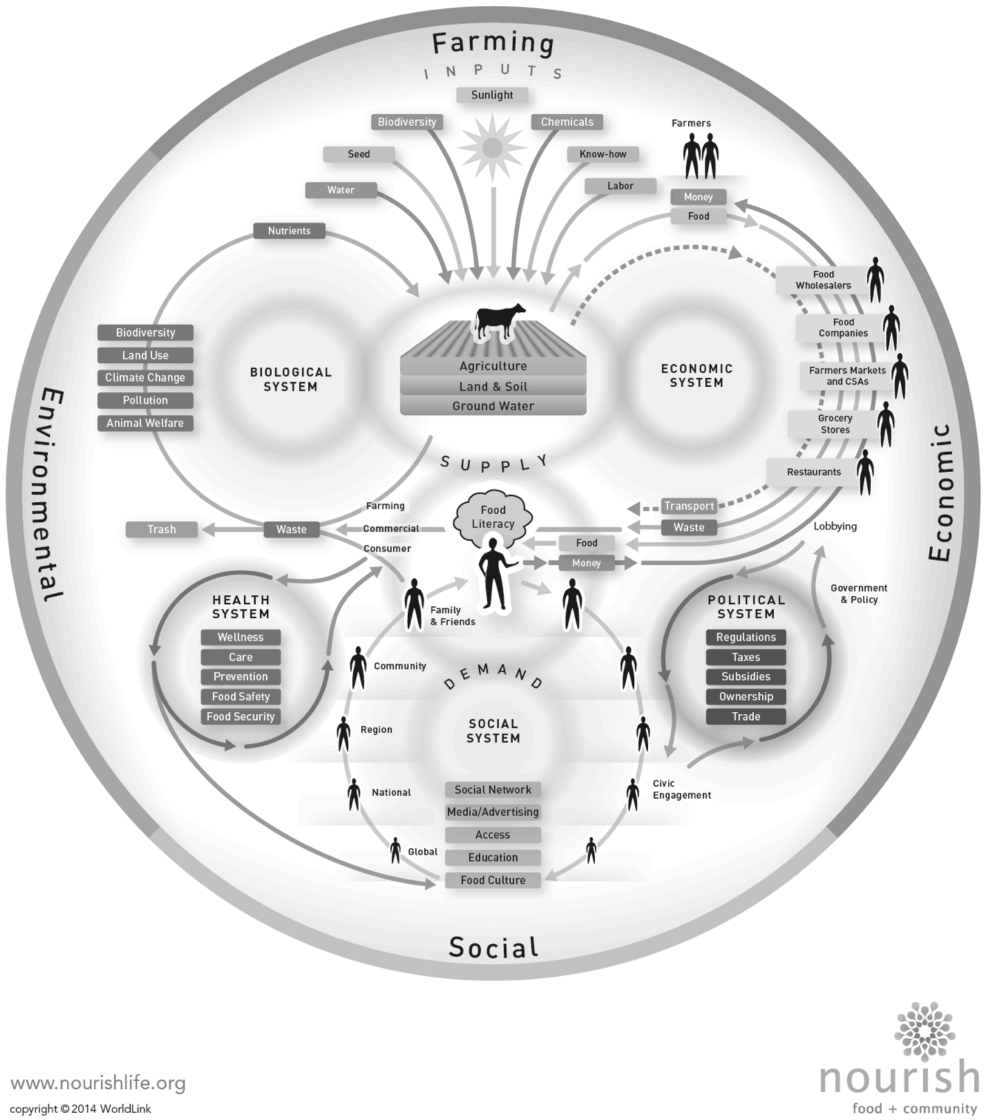

Figure 1b: Nourish Food System Map (www.nourishlife.org in Neff and Lawrence 2015: 4) copyright © 2014 WorldLink

Figure 1c has a narrower focus on factors affecting food and nutrition security. It describes ten pathways linking the agri-food system, the environmental system, and the health/disease system to individual health and security outcomes. This diagram prompts questions about causal connections between sectors that generate food and nutrition outcomes.

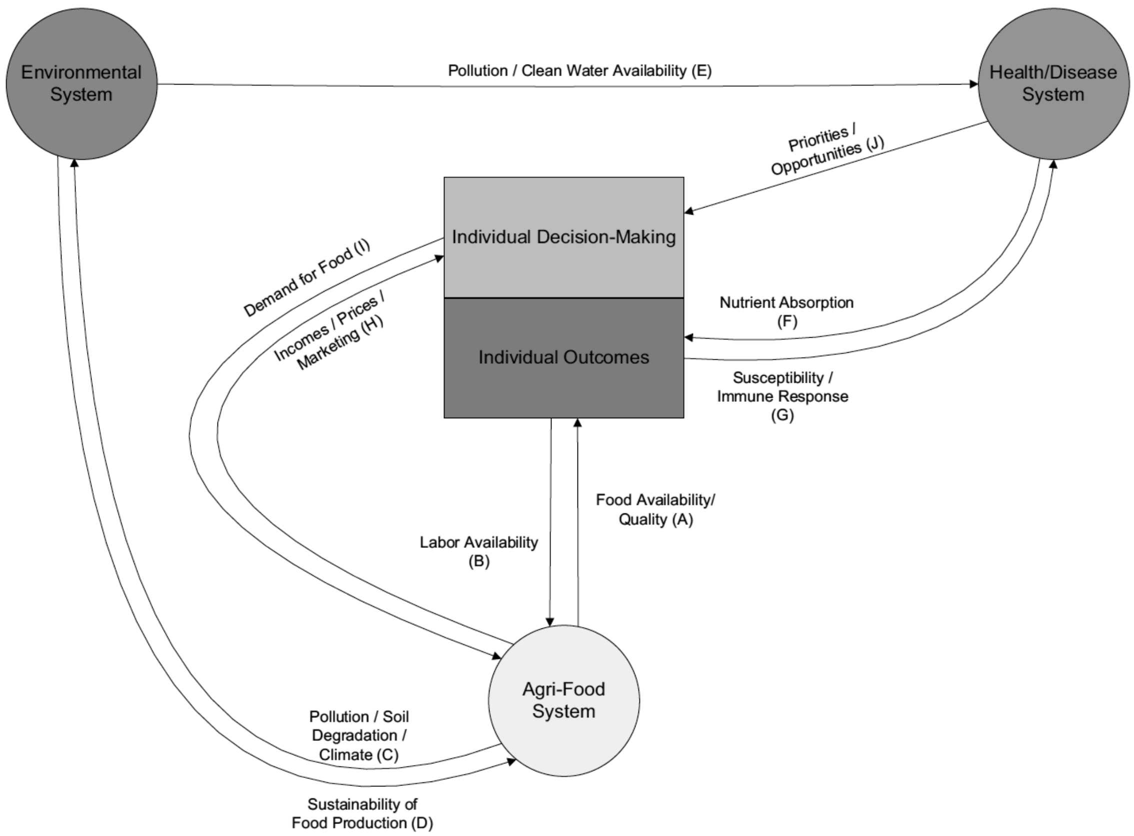

Figure 1c: A systems framework for food and nutrition security (Hammond and Dubé 2012: 12357) copyright © by the National Academy of Sciences

Conceptual diagrams such as these are high-level, aggregated ways of seeing food systems, each with a different purpose. Figure 1a frames a general theory about what governs food system vulnerability. Figure 1b shows that diverse food system components are related. Figure 1c begins to specify pathways by which one sector causes changes in another to affect food and security outcomes. They each focus on different high-level questions. Identifying specific shocks such as extreme weather events and stressors such as the spread of new pests and diseases and exploring how they would play out to affect food supply and other system outcomes, however, requires a more functional or operational representation of the mechanisms and causal links in the food system.

In the following sections, we use the structural thinking tools of system dynamics to translate general influences, associations and links in these kinds of conceptual models into causal relationships. Specifying material and information flows helps identify places where system components (such as food, nutrients, money, knowledge, or production capacity) accumulate. This helps identify potential bottlenecks and points of vulnerability.

Overview of the system dynamics modeling approach

The starting point for a system dynamics analysis is an observed or anticipated trend over time that is considered problematic. The goal of analysis is to describe the stocks, flows, and feedback relationships that generate the behavior of concern. After the system structure is validated, it can be used to experiment with the system's potential response to planned policy interventions or unplanned disturbances.

A system dynamics analysis follows a set of steps to develop a model that can be used to examine the underlying causes of the problematic trend (e.g., Richardson and Pugh 1981; Sterman 2000). These steps are:

1. Problem definition

Identify the observed or anticipated trend or set of trends over time that is considered to be problematic. System dynamics is appropriate for problems that can be framed by fluctuations in one or more variables over time. The purpose of subsequent analysis steps is to explain what causes the dynamic behavior of concern, and often to identify policy interventions that could change the trends in a more desirable direction.

2. System conceptualization

Identify the stocks, flows, and causal relationships among variables that generate the problem of interest. The central principle of system dynamics is that the structure, the "plumbing" of the system that describes the essential components of the system and the way they are connected, gives rise to the system's pattern of behavior. In the system conceptualization step, theory, data and general knowledge about how the system works, often contributed by stakeholders in the system, are used to develop an integrated picture of the system that generates the system's behavior over time. The structure is the hypothesis about what generates the system's dynamic behavior. It is called the *dynamic hypothesis* about what is causing the problematic trend. System conceptualization can be qualitative, using diagrams to visually represent different types of variables and the relationships among them, or operational, in which mathematical equations describe relationships among variables. Mapping the system's causal structure generally starts by working backward from the identified problem variable, asking what other variables cause the variable of interest to change, then continuing backward variable-by-variable. The point is to build the system structure by tracing from the problem behavior outward along chains of cause and effect, rather than from the system boundary inward. This is described as modeling the causes of the problem, rather than modeling the system. Modeling the causes of the problem makes it easier in subsequent steps to analyze the potential impacts of planned policy interventions and unplanned disturbances.

3. Model validation

This step includes a number of techniques to test the logic of the proposed model relationships against what is known. These can include confirming the face validity of a diagram with stakeholders or other experts, or running an operational version to test consistency of the assumptions in the model. If the model is in operational form, a key test is to simulate the model and compare its behavior with observed or anticipated system behavior.

4. Model analysis

If a simulation model is produced, it can be used to test the response of the model to possible disturbances. Disturbances could be either shocks or stressors, or deliberate policy interventions or structural changes intended to improve the system's capacity to buffer shocks or stressors.

These steps follow and build on one another, but they are also iterative, particularly between model validation and system conceptualization. If a proposed system structure cannot be validated, it is revised and then tested again.

In the following analysis, we use Steps 1 and 2 to identify, describe and discuss causal mechanisms that underlie several parts of the food system. By doing so, we show how system dynamics diagramming methods can be used to further specify the elements and relationships in conceptual diagrams such as those in Figures 1a, b, and c.

Application to Food System Vulnerabilities

Based on Marten's (2015, this issue) definition of vulnerability above, we frame the problem of food supply vulnerability as the concern that the food system might be subjected to shocks or stressors that would cause a normally stable food supply to catastrophically or permanently decrease from its normal or desired level. In this section we start by representing Marten's vulnerability definition graphically, then work outward from the problem definition to build the structure likely to be generating the problematic trends. We show three levels of progressively more formal diagrams of model structure. The first level of formalization is a high-level concept map similar to those shown in Figures 1a, b, and c, but is specifically tied to the problem definition graph. It shows the key relationships between three major sectors in the food system—people, food and environment—and locates the food supply indicator relative to other system components. It orients the viewer to the major sectors and identifies key stocks by sector. The second and third maps expand the causal and operational details in the sectors. The third map focuses particularly on the interaction of these pathways with sources of adaptive capacity.

We discuss each map in two subsections. The first describes the system structure at that level; the second discusses how vulnerabilities are revealed by that structure, and how they might be amplified or dampened. We analyze each level separately, and then discuss the analysis as a whole at the end of the paper.

Problem definition

The graph in Figure 2 illustrates the set of food supply trends implied by the definition above. The first is the normal or desired trend in food supply we would expect to see in the food system if it is operating "normally. " The solid, roughly horizontal line describes the expectation that, over time, food supply in a high income country (indicated by, e.g., *food available for consumption)* would remain basically stable around a level considered good or desirable for that system, with minor fluctuations. For a developing country with a rapidly growing population, *food available for consumption* might be rising over time, and would be represented by an increasing trend over time.

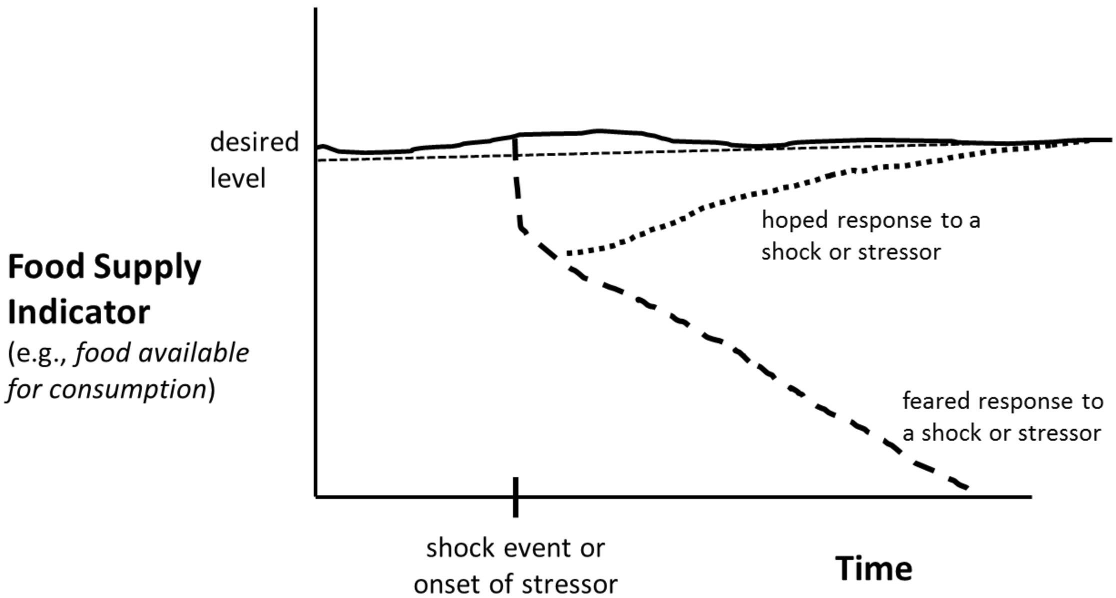

Figure 2: Graphical form of Anticipated Food System Problem

The second trend implied by the definition represents the way food supply would be expected to respond to a particular disturbance. The decreasing dashed line represents the concern or fear that a sudden shock like an extreme weather event or major power outage would lead to a sudden decrease in food supply. The exact shape of the response would depend on the type of shock and the point at which the indicator was measured. An event that destroyed food in the system close to consumers would affect food available to consumers more quickly, for example, than a shock that affected the supply chain farther away from the consumer. A stressor would likely have a more gradual onset. The magnitude of the decrease would be related to the severity of the disturbance. We would expect the food supply indicator to decrease in response to a major shock or stressor, but hope that the system could recover. The steadily decreasing dashed line represents the fear that the system would not be able to recover from the disturbance. The dotted line represents the desired response of the system, returning the food supply to its pre-disturbance stability. The deviation of the food supply indicator from its "normal" behavior, the solid line, would be a measure of the system's vulnerability to that disturbance. The system would have a low vulnerability to a particular disturbance if the food supply would not deviate much from its undisturbed pattern and returned quickly. It would be highly vulnerable to a particular disturbance if it would deviate significantly from its undisturbed behavior.

System conceptualization I: High-level sector relationships

System structure I

To map the structure underlying food supply, we start with *food available for consumption* and work backwards to identify the high-level relationships that cause this food supply indicator to change. *Consumption* decreases the stock of *food available for consumption*, food *moved to retail* from the stock of *food in processing and distribution* increases it. Figure 3 shows an initial abstraction of the food production, processing, and distribution supply chain generating *food available for consumption.* The amount and characteristics of food products that emerge at the consumer end of the chain are a function of the amount and characteristics of resource inputs available at the beginning and along the chain.

Continuing to work outward from the food chain shows the connection between the Environment Sector and food production, in which food *production* is a function of *resources available* and *resource condition*. Environmental resources needed for food production include land, water, and nutrients. The condition of resources can vary from optimum for food production to degraded, affecting the productivity of the resource. The condition of resources as well as the amount of resources used is a function of Food Sector activities, including farming practices, pollution from food production, processing and transportation, as well as waste from multiple food activities. Activities in the Food Sector are also a function of Population Sector elements. The size of the *population* and other characteristics such as population distribution and food preferences influence demand for food products, type of processing, networks of distribution hubs and retail sites, and consumption. Food Sector activities also depend on labor and labor productivity, which are Population Sector characteristics related to *population* and *health of population.* Food-related human health is, in turn, a function of outputs from Food Sector activities.

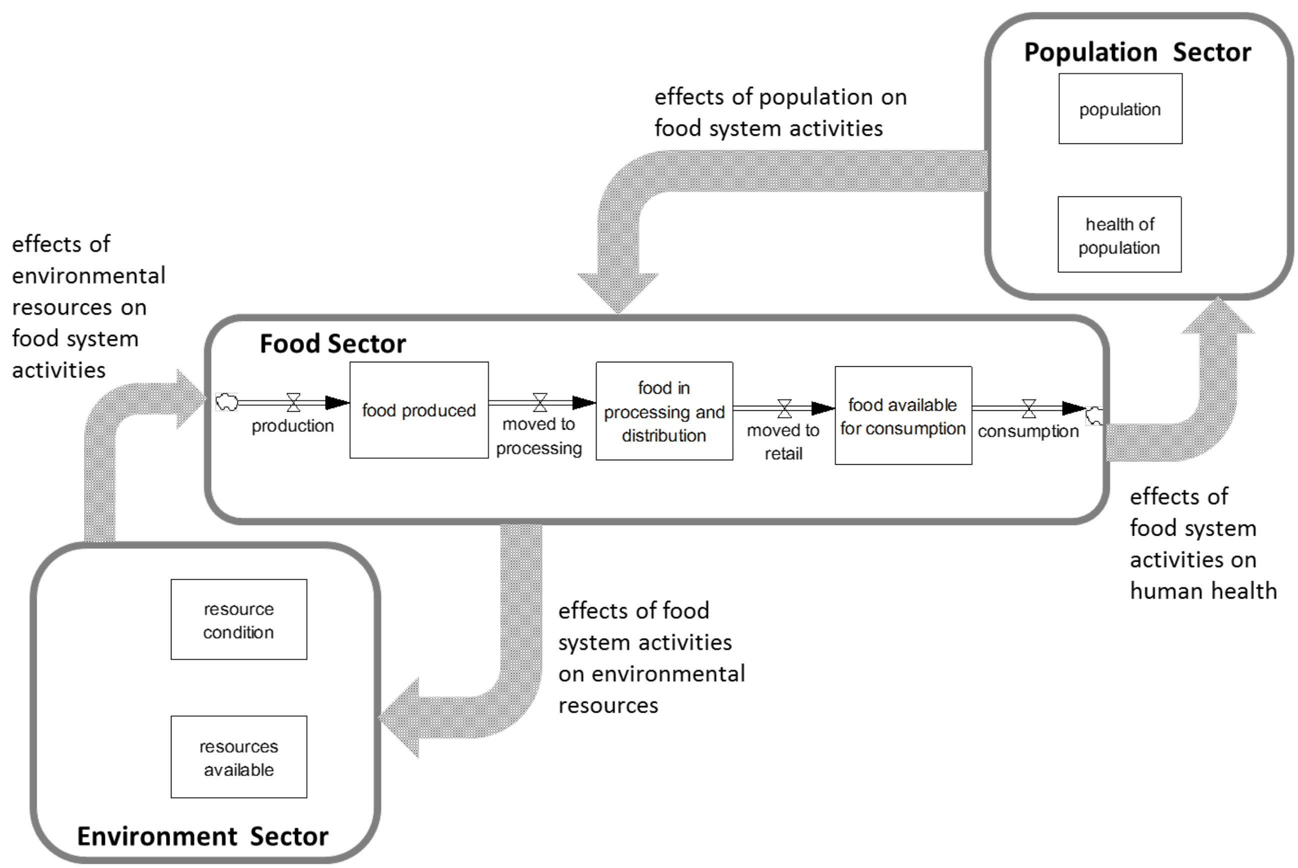

Figure 3: Sector diagram showing relationships between population, food and environment sectors

Analysis of system behavior and vulnerability I

The simple representation of the food system in Figure 3 shows that there is feedback between each sector and that the relationship between the population and environment sectors is mediated by the food sector. The population sector provides the demand for and receives outputs from the food sector. Population both motivates the activities in the food sector through demand, and makes them possible by providing labor for production, processing, distribution, and other activities. The environmental sector provides the fundamental resource inputs to the food sector and bears the consequences of its activities through poor use or pollution.

The structure of the food sector supply chain means that most consumers of its outputs never interact with its environmental inputs. Feedback between consumers and food sector effects is limited and indirect. The longer the chain of producing, processing, distributing, and preparing food for consumption, the more distant consumers are from the effects of the food sector activities on the environment. Consumers may not feel environmental degradation caused by food sector activities, and any changes consumers might demand in how food is produced may be masked or disregarded in the food sector (Sundkvist et al. 2005).

Additional sources of instability are rooted in the structure of the food sector. The food sector activities of food production, processing and distribution and consumption form a supply chain. Supply chains, which are fundamental to a wide range of systems, are subject to instability and oscillations. A supply chain consists of stocks, in this case the amount of food that has been produced and then the inventory of food products in later stages, together with the decision rules used to manage them. These decision rules aim to keep the stocks in the supply chain at target levels, compensating for the regular outflows and for unanticipated disturbances. Under steady conditions, where decisions about production and inventories along the chain are balanced with relatively steady demand, the system can operate smoothly. However, even minor disturbances can lead to instability. In the food sector, there are important delays between the initiation of an action to control a stock level and the result. With disturbances, this creates a supply line of unfilled orders. Failure of food sector stakeholders to take these time delays into account can introduce oscillations, amplification and phase lags (Forrester 1961; Sterman 2000). In a food system with many product choices and a diversity of food sources, distributor and consumer substitutions may buffer the effects of some shortages. Other stakeholders in the system may increase their desired stock levels, to increase storage in the system as a buffer against shocks. Holding excess inventory reduces order oscillation and amplification. However, Croson et al. (2014) show that this is not sufficient to eliminate underweighting of the supply line of unfilled orders and thus to eliminate oscillations.

System conceptualization II: Expanded stock-and-flow map

System structure II

In this section we expand the conceptual model from Figure 3 by further specifying the stocks and flows that underlie the variation in the stock of *food available for consumption* over time. A stock is something that accumulates over time. Stocks can represent tangible items, such as the amount of food in storage or the size of the population, or intangible quantities, such as the level of concern about food additives or trust in food safety organizations. Stocks are represented in Figures 3, 4, and 5 by boxes. Flows are the inputs to and outflows from the stock over time, such as the rate of food production or consumption. Flows are represented by double arrows (“pipes”) with valves that regulate the flow. Clouds at the end of pipes and arrows indicate sources and sinks of material flow that are outside the system boundary.

The starting point for the map in Figure 4 is again the stock of *food available for consumption* from Figure 3. Although there can be significant issues concerning access to food between this supply and what the consumer actually consumes, the point of departure for this purpose is the supply itself. Similar to the process followed in the previous section, we start with the observed or anticipated problematic trend over time.

To describe the system that causes the stock of *food available for consumption* to vary, we start with the proximate variables: *food available for consumption* increases when consumers purchase food from retail stocks (governed by the rate of *end user purchasing and preparation*) and decreases when it is consumed (governed by the rate of *consumption*). We then follow the same process backwards down the food supply chain through distribution, processing and production. The amount of food in each stock is a function of the amount added to that stock minus the amount removed over time. Food flows between stages are influenced by a number of factors. Production requires a set of resource inputs that can come from a range of sources, including nutrients, water and energy, as well as technology and labor. Processing and packaging also require technology, labor, and energy, as well as resources for ingredients added during processing and resources needed for packaging. Distribution requires labor and energy for transporting and moving processed food to retail outlets. The consumption phase commonly requires additional labor and energy to prepare food to be eaten. The length of the food chain varies for different foods depending on the amount of processing, packaging and preparation. Some foods have more processing and distribution stages; some have fewer, such as when consumers buy food directly from producers. Food is lost and wasted at each stage in the food system. In modern industrialized food systems, most food loss and waste occur off the farm, after initial processing. Food waste is high in retail, food service, and homes and municipalities (Gustavsson et al. 2011). Figure 4 shows the essential elements of the stock-and-flow structure, but omits some connections for visual clarity. It is important to keep in mind that this diagram is a general overview intended to illustrate the form of a stock-and-flow diagram. A diagram for examining food supply vulnerability in a particular system would include the elements specific to that system.

Analysis of system behavior and vulnerability II

Expanding the Food and Environment sectors shows several entry points that expose the food supply system to disturbances from outside the system. It also shows a key feedback relationship that can convey certain external or disruptions throughout the system. Specifically, the need for inputs of labor at various stages closes the loop between food consumption, population health, food production and processing, and food available for consumption. This feedback mechanism has the potential to amplify disturbances to food supply that are significant enough to affect population health. Decreases in food supply that lead to decreases in health further decrease labor available for food chain activities, and could decrease supply even further.

Entry points for exogenous shocks or stressors

- **Food production.** (*SHOCK/STRESS reducing food produced*) Large-scale disturbances of food production include weather- or pest-related crop failures, livestock diseases such as avian flu and bovine spongiform encephalopathy (BSE) that lead to the removal of large numbers of animals from the food supply, or contamination with chemical pollutants, bacteria or other pathogens that lead to recalls and destruction of food in production or in other stages in the supply chain.

- **Human health.** (*SHOCK/STRESS reducing population health*) Flu pandemics or other widespread disease outbreaks first reduce the productivity of the labor force and, if severe or long lasting, could also reduce the number of people in the labor force.
- **Environmental resource availability and condition.** (*SHOCK/STRESS affecting resources available*, *SHOCK/STRESS affecting resource condition*) Long-term stressors such as climate change can affect the condition of resources directly through changes in temperature and moisture availability, and indirectly through changes in pests and pathogens. In some places, rainfall may increase, but lead to soil and nutrient erosion in systems not adapted to higher precipitation. Shocks such as floods or other severe weather conditions can reduce the amount of resources such as land or water available for production. Volcanic eruptions or major dust storms could reduce sunlight needed for photosynthesis.
- **Energy availability.** (*SHOCK/STRESS reducing energy available*) Every process in the system depends on a consistent and reliable input of energy. Fuel is needed for running equipment that produces and harvests food as well as transporting resource inputs and food products; energy is needed for processing food; energy is needed to keep food products cool during transport and in storage to prevent spoilage and waste; much of the food we consume requires energy to prepare it for consumption. External disruptions to fuel imports or the energy grid would ripple quickly through the system.
- **Transportation capacity.** (*SHOCK/STRESS reducing transportation capacity*) Severe weather events or human activity that destroys transportation infrastructure or disrupts transportation services such as closures of ports of entry for food imports, or roads or rail lines would affect all the flows of products in the food supply chain.

Internal or endogenous sources of system destabilization
In addition to external disturbances, this expanded stock and flow diagram shows how the system can be vulnerable to elements in the system structure itself.

- First, the expanded and more realistic representation of the processes in the food sector disaggregates the three basic stocks from Figure 3 (*food produced*, *food in processing and distribution*, *food available for consumption*) into several stocks. Any addition of stocks in a supply chain increases the amplitude of potential oscillations by increasing the difference between actual and desired production and thus creates more potential instability in the food system. Additions of stocks in a food supply line arise from increasing specialization and the resulting additional processing steps, which is typical for modern food systems (Sundkvist et al. 2005).
- Segments of the supply chain, e.g., the agricultural production segment with the *production* flow and the *food produced* stock, exhibit the structural characteristics responsible for the occurrence of commodity cycles (Meadows 1970). Commodity cycles arise from the interaction of the physical delays in production and capacity acquisition with boundedly rational decision making by food sector stakeholders (Sterman 2000). For readability, Figure 4 does not show the capacity stocks (i.e., machinery and infrastructure) relevant for agricultural production and all subsequent segments of the food sector. Nevertheless, shocks and stressors such as increased price volatility or changes in demand, significant drops in inventory, e.g. due to energy failure or widespread pests and diseases, introduce and amplify oscillations to food systems by increasing the difference between actual and desired production and actual and desired production capacity, respectively (e.g., Conrad 2004).
- While exogenous forces can disrupt transportation infrastructure and affect the movement of food and food products from agricultural production to consumers, the structure of the system

can make things better or worse. One example is that the length of a supply chain can increase its vulnerability to exogenous disruptions. Greater emphasis on local food sources is being promoted as a solution to what some consumers perceive as too great a separation between themselves and the source of their food (Seyfang 2006). Decreasing 'food-miles' is thought to increase food quality and decrease environmental pollution. However, decreasing food-miles may not have the benefits envisioned (Edwards-Jones 2010, Edwards-Jones et al. 2008), and may even have unintended negative consequences. Food system analysts in Australia are concerned that shifts to local food sources may erode regional infrastructure and leave local communities vulnerable if local sources fail (Larsen, pers. comm.). In Switzerland, where a large part of the calories consumed are imported, changes to consumption patterns can have far-reaching impacts on national food production (Kopainsky et al. 2015). Effective food systems thus rely on diversity in the length and kind of supply chains.

- Another example is that reliable food provision requires food to move through the various stocks in the food sector, that is, from the stock of *food produced* all the way to *food available to consumers*. The reliability of this process not only depends on the flows linking the various stocks but also on the average residence time of food in each of the stocks. Low residence times indicate fast movements of food through the chain. This makes the food system efficient as long as flows are left uninterrupted. Low levels of stocks, however, can affect food provision very negatively in situations where inflows are interrupted or stocks are depleted in the course of environmental, economic and social shocks. In the U.S., as distribution networks have increased, the amount of storage has decreased, raising questions about the effect of a prolonged fuel shortage or disruption in transportation. Addressing this vulnerability by increasing storage might create tradeoffs between increased buffering capacity against exogenous shocks on the one hand and increasing amplitude of oscillations in the supply chain on the other hand. Recent literature on stocks, markets, and policy confirms the need for better understanding and analysis of the role of food stocks and their management (Abbott 2014; Galtier 2014; Lines 2014).

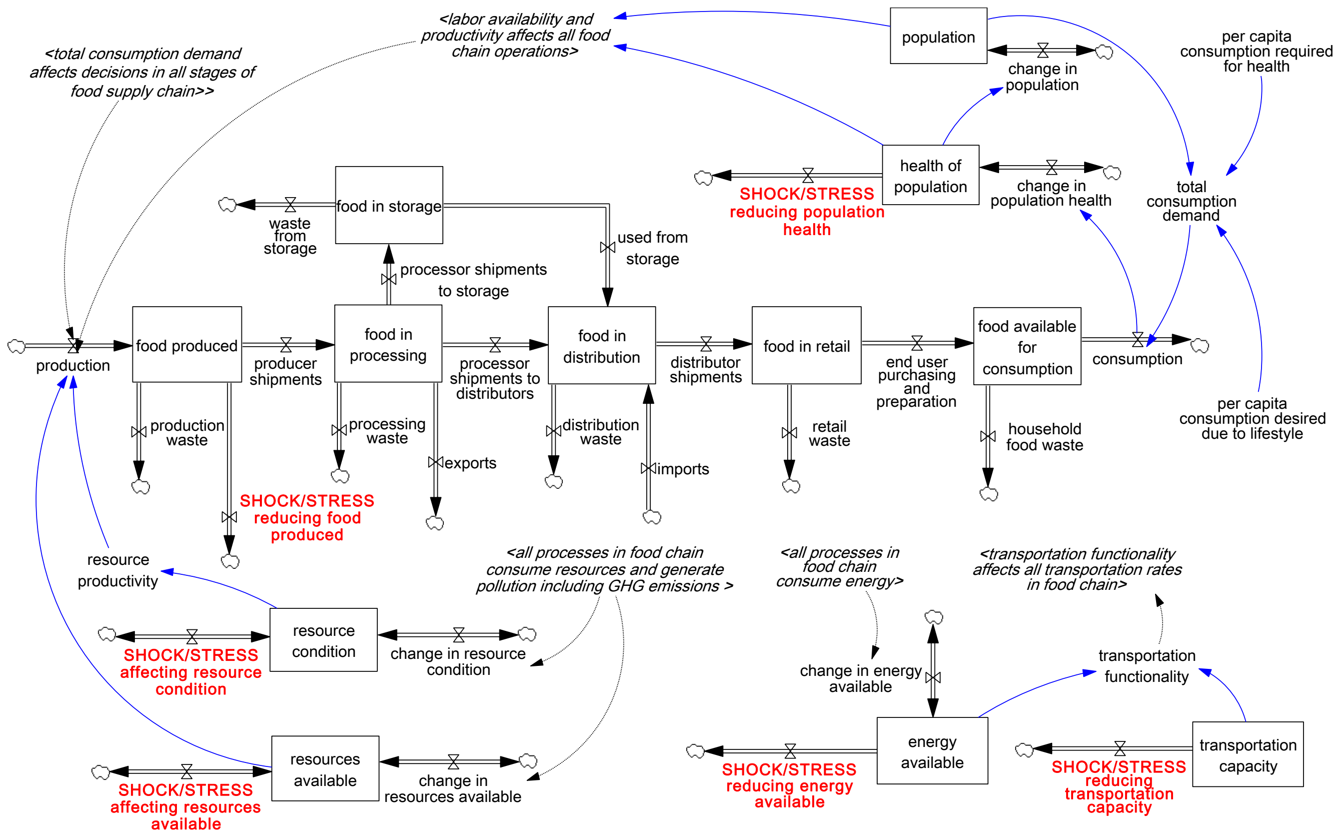

Figure 4: Stock-and-flow overview of a generic modern food system indicating sources of exogenous variability. Some links are omitted for visual clarity.

System conceptualization III: Focus on causal connections and feedback details

System structure III

System conceptualization levels I and II introduced some endogenous sources of vulnerability, that is, vulnerabilities that are created, amplified or moderated by internal system structure. This section further specifies the connections between environmental resources and food production. It illustrates the method of specifying causal links and revealing feedback mechanisms. In these diagrams, a single lined arrow connecting two variables represents a causal link. A causal link indicates both the direction of causality—that a change in the variable at the tail of the arrow causes a change in the variable at the head of the arrow— and whether the two variables change in the same (+) or opposite (-) direction. Thus the link *between investment to high external input* and *success of high external input* in Figure 5 would read: "as *investment to high external input* increases, *success of high external input* also increases and as *investment to high external input* decreases, *success of high external input* also decreases".

The starting point for the map in Figure 5 is again the stock of *food available for consumption,* but to explore the connections between the food and environment sectors in more detail, this map begins with a focus on *food produced*, the first stock in the food chain that leads to *food available for consumption.* This diagram maps a portion of the causal structure that explains how *food produced* varies over time. Food production is clearly dependent on environmental resources available for production (such as agriculture land, water, and soil nutrients) and the productivity of those resources. The productivity of those resources often depends heavily on external inputs, especially in high income countries. This reliance increases with increasing consumption of meat, a particularly resource-intensive human food. As Rivers Cole and McCoskey (2013) note, consumption of meat increases with increasing income. Meat production is likely to put substantially more pressure on global environmental resources as the emerging economies and demand for meat continue to grow, further increasing reliance on external inputs. Such reliance on external resources may make food systems more sensitive to external shocks, and therefore, more vulnerable (Ericksen 2008). In the agricultural production stage, external non-renewable resources include synthetic fertilizer, pesticides, hybrid seed, fossil fuel-based energy sources, and partly also water. In this section, we examine causal mechanisms that might create but also mask vulnerability of food supply to the availability and impacts of external non-renewable resources.

Resource productivity is also, at least partly, determined by the condition of environmental resources (for readability, intermediate variables such as soil fertility and the nutrient cycles that link *relative resource condition* to *resource productivity* are omitted from Figure 5). The flows affecting the resource condition are determined, among other things, by the implemented agricultural production system. Agricultural production systems are characterized by the type and amount of external inputs necessary to support production, by their productivity, and by their environmental impacts. In this example, we differentiate between two main agricultural production systems (e.g., Aune 2012):

- **High external input production systems.** These are characterized by a commercial market orientation, use of improved high-yielding varieties, mechanization with low labor intensity, almost complete reliance on external synthetic inputs such as fertilizers, pesticides, and pharmaceuticals in livestock production. High external input systems tend to overexploit, and degrade productive resources (e.g., Tilman et al. 2002).
- **Low external input production systems**. Low-external-input farming reduces as much as possible the use of external inputs like pesticides, herbicides and synthetic fertilizers and replaces them with internal inputs. Diversification of crops and animals, crop rotation, and organic matter cycles are key concepts and help rebuilding and maintaining stocks of productive resources. Techniques vary from the use of traditional knowledge to use of modem bacterial herbicides and insecticides that replace their synthetic equivalents (Milner and van Bueningen 1993). Low external input agriculture is less capital- but more labor- and knowledge-intensive.

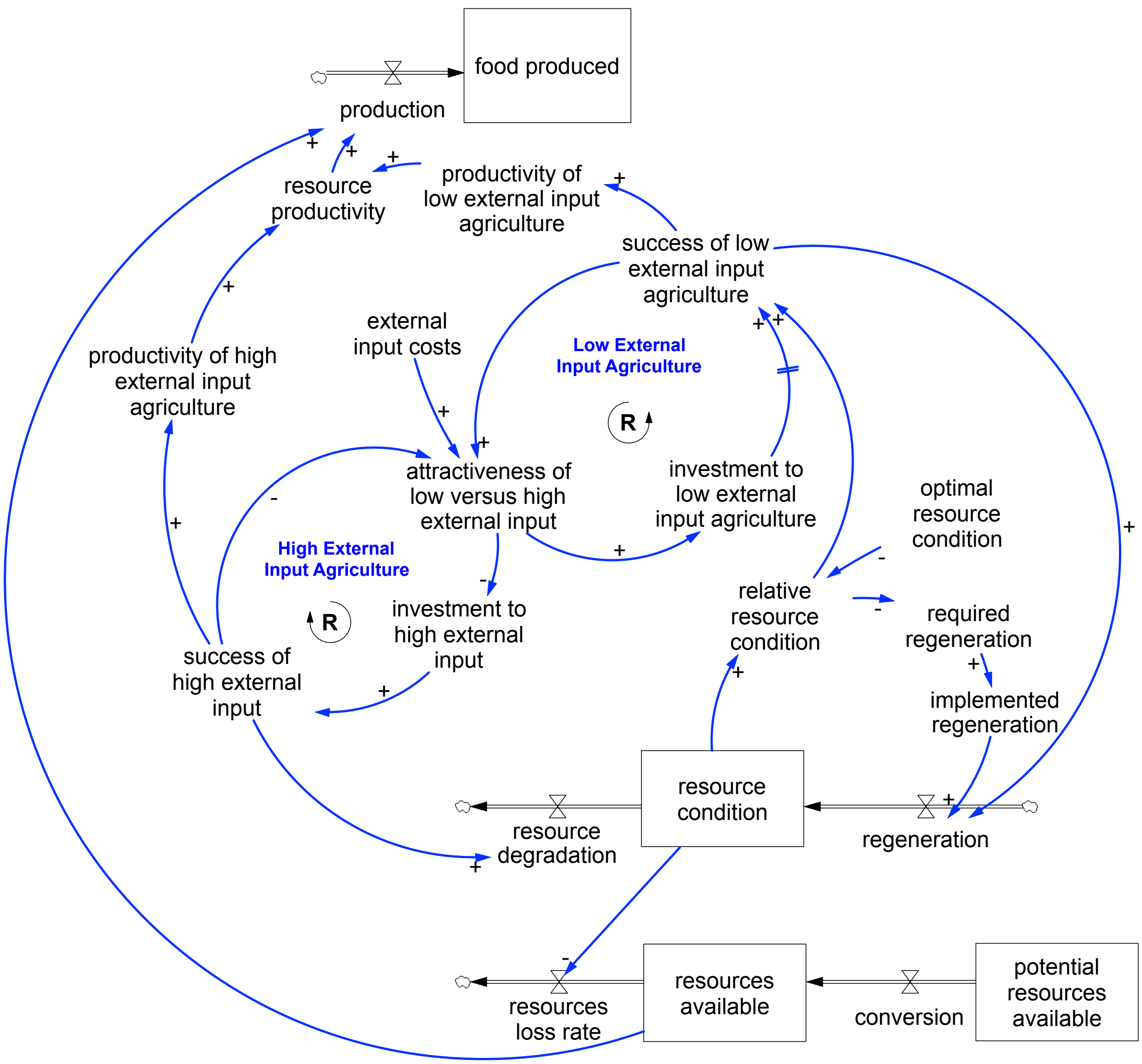

Figure 5: Feedback mechanisms that unveil and explain vulnerability of food systems to the availability and impacts of external non-renewable resources

Figure 5 shows how these two systems can be represented in a diagram that includes both stocks and flows and causal loops. The causal mechanisms shown in Figure 5 describe the extent to which each production system is implemented, based on the logic of the "success to the successful" archetype (Senge 1990). The variables *investment to high external input* and *investment to low external input agriculture* represent the potential productivity (e.g., yield) of the two production systems, while the variables *success of high external input* and *success of low external input agriculture* represent the realization of the potential productivity of the two systems. Success of each system depends on investment in the system. Investment, in turn, is determined by how attractive the production systems are relative to each other, which is again a function of how successful each system is (e.g., Rozman et al. 2013). In this way, the production system with the higher investment dominates and the other fades away. There is a delay between investment and success of low external input agriculture in Figure 5 (indicated by the double slash on the causal link). This represents the time it takes to develop the necessary skills for the use of low external input techniques and practices with farmers (Milner and van Bueningen 1993).

Analysis of system behavior and vulnerability III

The feedback mechanism in Figure 5 shows that when fossil fuel is available and inexpensive (*external input costs* are low), there is strong incentive to continue to use external inputs such as fertilizer and pesticides to boost crop yields (Sundkvist et al. 2005). Lower external input costs decrease the attractiveness of low external input agriculture and increase the attractiveness of high external input agriculture. The success of the high external inputs production paradigm reinforces itself and forces the alternative production paradigm, one that treats natural resources in a regenerative way, into a reinforcing spiral away from low external input production – a vicious cycle.

Once the costs of external inputs increase and their availability decreases, it takes a long time for the low external input agriculture paradigm to become effective. The dominance of the high external input paradigm erodes the knowledge base necessary for a successful implementation and continuous adaptation of the low external input agriculture paradigm. In addition, the success of low external input agriculture depends on the health of natural resources (*resource condition*) as this production paradigm has no way of substituting synthetic for natural resources to increase productivity. These barriers to a swift transition from the high to the low external input agriculture paradigm indicate a hidden source of vulnerability of food systems and especially one that is time consuming to overcome.

The health of natural resources (*resource condition*) is a proxy for options for adaptation and alternative solutions in case of changes in the environment such as climatic shocks or pests and pathogens. Low health of natural resources indicates low diversity and diversity is important for absorption of shocks, adaptation and alternative solutions (Berkes et al. 2003). The diversity inherent in low external input farming systems makes it more likely that the farming system can cope with such changes.

The farther away the natural resource base moves from an optimal level of natural resources, the greater the need for regenerating natural resources (*desired regeneration*). Regeneration, however, is limited by two main factors (not shown in Figure 5 for readability purposes). One is the fact that the use of external inputs lowers the motivation of food system actors to rebuild and maintain the natural resource base of food systems as natural resources, at least in the short run, can easily be substituted by external inputs (Sundkvist et al. 2005). Another is the increase in the time to perceive changes in food-related environmental resources as distances from production to consumption grow. Greater distances (more food-miles) impede the flow of information in the food system and decrease the possibilities to make informed decisions on management and consumption (Sundkvist et al. 2005), that is, desired regeneration is reduced.

Discussion

The objective of this paper was to demonstrate how system dynamics diagrams can be used to show where complex food systems might be vulnerable to external disturbance and how causal pathways transmit their effects. We developed three progressively more specific maps describing the causal structures. The first map (Figure 3, system conceptualization I) is a high-level conceptual diagram connecting the food supply chain with the population and environment sectors, identifying feedback relationships between sectors and key stocks by sector.

The next two maps show examples of how system dynamics helps us think about causal relationships important for understanding food system vulnerabilities by describing causal links by type. One type of causal link is material flow, in which the level of a variable changes over time as a function of the rates at which quantities are added and removed. Another type of causal link is information flow, which can be thought of as decision rules, or signals, that govern the way flow rates change. The second map (Figure 4, system conceptualization II) focused on a section of the food system where the causal relations are mostly material flows. The third map (Figure 5, system conceptualization III) focused on a section of the system in which information flows make up a large part of the causal structure and shows how causal links can connect to form feedback loops. This example describes feedback loops that determine the extent to which nutrients required for agricultural production are sourced from external versus internal inputs. Similar analyses could be done to examine the diffusion patterns of alternative technologies or consumption patterns, organizational structures in the supply chain, or price formation and market dynamics, if they were relevant to explaining the variation in food supply in a particular application.

We used these three maps to discuss pathways by which shocks and stressors affect food systems. A qualitative analysis of the maps showed that food system vulnerability does not only or automatically result from exogenous shocks. Instead, it can be either intensified or reduced by the interaction of feedback loops in the food system. These kinds of causal maps help focus thinking about vulnerabilities on the structure of the system rather than on events that might shock the system.

How can this approach promote food system resilience?

In addition to raising the question of how food systems in high income countries might be vulnerable, Marten (2015, this issue) also asked what specific practical actions 'scientists, teachers, and other environmental and food-system professionals could take in research, education, community action, or other means to make the food system more resilient.' The main product of this paper is a framework with examples that can be applied to any food system to identify types of disturbance, where they would occur, qualitatively what effect they would have, and whether they would likely be amplified or absorbed by the system. The framework facilitates the generation of qualitative system maps, which serve as an initial step for exploring structural features that generate dynamic behavior. They provide a parsimonious view of links between population, food activities, and environmental conditions that is transparent and internally consistent, and allows initial exploration of tradeoffs in the system (Kopainsky and Luna-Reyes 2008; Repenning 2002). The maps developed here present a general overview of industrialized food systems for the purpose of illustrating how to use system dynamics diagramming techniques to examine food system structure. They show general system feedback mechanisms and points of vulnerability. To identify specific actions and potential policies for increasing the resilience of any particular food system, the structural maps would have to be customized to that system. However, although our paper focused primarily on *how* to think about food supply vulnerability rather than the question of *what* can be done to promote food system resilience, the use of system dynamics diagrams to make food system structure visible does have practical implications for promoting resilience.

Causal loop and stock-and-flow diagrams are often used as an intermediate step between internal representations or verbal descriptions of a problem and a formal simulation model (Lane 2008). Researchers use structural diagrams to organize their knowledge about a system and as a first step toward developing an explanatory model, managers and policy-makers use diagrams to identify leverage points in the system for intervening to change the system's output or outcomes. But visual representations have value on their own for facilitating individual and collaborative reasoning (Black 2013; Hoffman 2011). Hoffman (2011:193) argues that diagrams allow individuals to 'reflect on something without being constrained by the limits of one's short-term, or working memory, clarify and coordinate confused ideas and implicit assumptions about a problem, identify knowledge gaps, play with interpretations, discover contradictions, distinguish the essential from the peripheral,' among other things. Giardino (2013:240) describes a diagram as "an *external representation* which is *potentially public*." It transforms an internal representation or mental models into a form that can be shared with others. In this way, they can serve as a platform for collaborative problem-solving. Black (2013) explains how system dynamics structural diagrams co-created by a group of stakeholders can serve as boundary objects, visual artifacts that allow stakeholders to locate themselves in the system relative to others and see how their concerns connect to the concerns of other stakeholders. These visual representations promote collaboration across disciplinary, social, or other boundaries. Diagrams can aid reasoning in groups by focusing the group's attention, stimulating the "negotiation of meaning" of the diagram, and fostering understanding of differing perspectives (Hoffman (2011:193). Hovmand (2014) develops system dynamics diagrams with community groups to facilitate collaborative problem-solving about issues as diverse as community health and access to financial institutions. These uses of systems diagrams—for organizing knowledge, developing a shared representation for collaboration, co-creating boundary objects to link diverse stakeholders, facilitating community problem-solving—are also applicable to issues of food system vulnerability and resilience. Diagrams that make the structure of these complex systems visible to consumers and other stakeholders can begin to engage stakeholders in discussions about food system vulnerabilities or actions to promote system resilience.

In policy-making and collaboration around action, qualitative maps can help shift the discussion away from ineffective single intervention approaches towards solutions more appropriate for complex problems (Finegood et al. 2010). In our example of the competition between high and low external input paradigms, for example, the map illustrates the continuously increasing dominance of one paradigm over the other. An implication of this for designing an intervention to promote resilience is that shifting this dominance, e.g. from the high external input to the low external input paradigm, requires a long-term perspective. Policy interventions need to strengthen research and development for low external input agriculture and knowledge accumulation with farmers and other food system stakeholders on how to implement such a paradigm. None of these processes shows immediate results that quickly increase the attractiveness of the low versus the high external input paradigm. Policy interventions to strengthen low external input agriculture thus need to be implemented over long periods of time and be substantial enough to shift the direction of the attractiveness loops in favor of low external input agriculture. This is different from prevailing policy approaches that aim for quick results to demonstrate their effectiveness. Special emphasis thus needs to be put on communicating the need for alternative policy approaches and on their preliminary success on small scales and in pilot cases.

This analysis started with a question about how apparently stable food systems in high income countries like the U.S. could be vulnerable to external disturbances that might disrupt the food supply. This vulnerability assessment asks, in essence: what are the threats to the stability and security of the existing food system, and how can we keep it stable? We suggest that the existing food system is not simply under threat from external disturbances, but that the internal structure of a system that provides diverse, inexpensive, and convenient products at the expense of intensive resource use and reliance on external inputs might itself not be stable for the long-term. This implies that further assessment of vulnerabilities should examine internal threats to food supply stability that arise from system structure more closely and find ways to make the system more sustainable, both independent of and in combination with external threats.

Additional resources

There are many sources for more information about system dynamics model formulation and philosophy. These include: Ford (2010), Richardson (2011), Sterman (2000), Vennix (1996), and Hovmand (2014). For examples of particular applications of fully operational system dynamics simulation models to food system issues, see the following: models of crop growth and management (e.g., Yin and Struik 2010), nutrient dynamics (e.g., Saysel 2014), soil degradation (e.g. Saysel and Barlas 2001), development of environmentally friendly farm systems (e.g., Belcher et al. 2004; Shi and Gill 2005), irrigation systems design and management (e.g., Saysel et al. 2002), food supply and security (e.g., Conrad 2004; Georgiadis et al. 2005), commodity markets (e.g, Nicholson and Stephenson 2014; Nicholson and Kaiser 2008), agricultural development policy (e.g., Kopainsky et al. 2015; Züllich et al. 2015) and vulnerability analysis of high versus low external input farming systems (Pedercini et al. 2015).

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Conflict of interest

The authors declare no conflict of interest.

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