Multiscale modeling of the food system

organized by
John Ingram and Mary Lou Zeeman

Workshop Summary

The workshop was facilitated by Ariella Helfgott[1], Stephen Lord[2] and Vanessa Schweizer[3]

[1] *Environmental Change Institute, University of Oxford.*
[2] *School of Mathematical Sciences, University of Adelaide*
[3] *Department of Knowledge Integration, University of Waterloo.*

Goals: The goal of the workshop was to elaborate a research agenda for developing a mathematically-robust conceptual model of the U.S. food system. This is a key component of a large-scale project to develop a hierarchy of models for food systems around the globe at multiple spatial and temporal levels. The overarching goal is scenario testing to inform intervention strategies for improving sustainable food and nutrition security for all people. One extreme of the model hierarchy will consist of complex systems of coupled, detailed models of food system activities (Figure 1 on page 9). The focus of this workshop was at the other extreme, where there is a pressing need for models at the conceptual level, to give insight into the overall structure of the system, and the relative strengths of inherent feedbacks. Without this structural overview, coupling of the more detailed system components lacks the coherence necessary for such a complex system.

Background: With about 1 billion people hungry [FAO2014], 2 billion with insufficient nutrients [Myers2014] and over 2 billion already overweight or obese [Ng2014], malnutrition is affecting the health outcomes of over half the global population; they are all food insecure. Many factors besides food production drive food and nutrition security [Ingram2011]. As diagrammed in Figure 1, the 'food system' refers to the entire set of *activities* by which calories and nutrients are grown, harvested, traded, processed, transported, stored, sold, prepared and eventually become the food we consume. Thus, food system 'actors' include producers, post farm gate 'food chain' actors and consumers. There are multiple feedbacks among these activities, resulting in the overall food security *outcomes* (availability of, access to and utilization of food). Meanwhile, current food chain activities are already seriously undermining the natural resource base upon which food security depends. These nutrition and environmental concerns point to inefficiencies in the *food system* as a whole. Better tools are needed to assess options for moving towards a sustainable, food secure society.

Participants: Since the overarching goal of the modeling effort is decision support (i.e. scenario testing to inform intervention strategies), it is fundamentally important that models are co-developed with food system experts and stakeholders (producers, industry, policy-makers, and consumers) to ensure the range of perspectives inherent in food systems is considered. It is also essential that mathematicians be full partners from the early stages of this effort, to help identify modeling structures emerging from the stakeholder discussion, intrinsic in the food system, that can be mathematically exploited to ensure that models across the hierarchy can interface in mathematically robust ways. Workshop participants therefore included experts and stakeholders from different levels of the food system; social scientists experienced in facilitating participatory processes with stakeholders; economists; and mathematical modelers collectively representing expertise in a range of modeling approaches, including ordinary differential equations, partial differential equations, multi-scale modeling, dynamical systems and bifurcation, stochastic systems, agent based modeling, data driven modeling, uncertainty quantification, fuzzy cognitive maps, cross impact balance analysis, bayesian belief models, stochastic optimization, network analysis and computational analysis of social media data.

Participatory process to define the food system: The workshop approach was a mathematical enrichment of the *participatory process* that workshop facilitators Helfgott, Lord and Schweizer have used to gather and map stakeholder perceptions. The participatory process enables a diverse group of stakeholders, with potentially conflicting interests and different levels of power, to collectively define the system of interest [Kok2009]. A participatory process typically takes one day, and yields a network model (directed graph) of the system as it is perceived by the stakeholders surveyed.

Thus, on Day 1, after an introduction to the food system, workshop participants were divided into three teams, and led through a participatory process to define the food system by facilitators Helfgott, Lord and Schweizer. The teams were carefully selected to make sure each had a range of scientists, stakeholders, economists and modeling expertise. Based on the food system overview, the three-fold goals of the Day 1 exercise were 1) to illustrate to the mathematical modelers how the participatory process works, and its potential for identifying structures by which quantitative and qualitative data might be used together in a model; 2) to illustrate to the non-modelers that without an underlying question to organize the modeling effort, it is impossible to identify and extract the relevant components of the system; and 3) to compare the networks developed by each team, to see consistent themes emerging across the teams, and the differences.

Policy questions to focus the modeling efforts: On Day 2, the need for policy questions to focus and organize the modeling effort was addressed. Participants worked in pairs to identify policy questions a food system model might help to inform. The full group then refined the questions, yielding the following list of 14:

1. What drives dietary inequality in the US?
2. What strategies can we implement to create a more self-sustaining highly urbanized population with few immediate agriculture resources in the environment?
3. How do we make market prices for food reflect the true cost?
4. How do we maintain adequate water supply for all stakeholders?
5. What can the US do to pre-emptively protect against disaster or attack on the US food distribution system?
6. How can agriculture in California represent food supply nationally by growing suitable crops that are wanted and needed in the diet?

7. If the US diet transitions to align with the USDA healthy eating guidelines what policies would facilitate that transition without increasing environmental impacts?
8. How would national regulation of greenhouse gas emissions impact food security in the US?
9. What is the role of US policies and programs in contributing to a healthy food system that operates within planetary boundaries?
10. How can we inform and empower consumers so they can make informed votes with their dollars about the systemic impact of their dollars?
11. How do we ensure equitable access to and availability of nutritious food for all to a growing population?
12. How does one capture the ethical dimension of hunger in modeling the food system
13. What are the technologies and resources (use of land, water, etc.) needed to sustainably and resiliently maintain and improve food security (of food produced by US)?
14. How will emerging economies (such as China) change the US food system?

A voting process (in which each participant could assign 5 votes in whatever distribution pattern they liked) was used to select three questions (questions 1,2 and 3) to focus on at the workshop. Each team was assigned a question, and tasked with revisiting the participatory process in light of their question (Day 2), and then designing a modeling strategy and research agenda for answering the question (Days 3 and 4). Participants were invited to move between teams after Day 2.

Team 1: What currently drives dietary inequality in the US?

Purpose. To further focus the modeling effort, additional goals were identified, associated with the team's question: 1) Being able to assess environmental or policy interventions via a model of dietary inequality would be useful. Example: how would American diets respond to an increase in the price of meat? 2) Identifying associations that are: heterogeneous, level-specific, or teleconnected across levels or scales that could motivate scientific inquiry about causality. 3) Trend analysis (current and future). 4) Decision and Inquiry support for local and regional decision makers.

Background. Many people in the United States are not well nourished, leading to a decrease in healthy years, and adverse effects for society and the economy. Rich understanding of dietary quality is multidimensional (calories, protein, vitamins, minerals, etc). Subpopulations also matter, i.e. by age, development stage, pregnancy (neonatal health, first 1000 days). Quality measures are an active area of research for nutritionists, and data availability may present a challenge. Food availability varies on spatial scales (diversity of foods, fruits / vegetables, fibers) and matters for individual outcomes. Consumer behavior is a complex response to a range of constraints, incentives, tradeoffs, policies, trends, culture, local influence, etc. operating at multiple levels across space, jurisdictions and time. Thus, this question focused attention on identifying relevant metrics, data, and scales at which drivers act.

Metrics. Existing metrics include 1) The Dietary Diversity Score (DDS), which comes in various forms including the Household Dietary Diversity Score (HDDS), the Individual Dietary Diversity Score (IDDS), and the WDDS (Womens Dietary Diversity Score). DDS is becoming mainstreamed into the Demographic and Health Surveys Program (DHS); 2) The Minimum Acceptable Diet, which has been established by the WHO and UNICEF and is used as a composite indicator to measure the quantity and quality of the infant diets ages 6 to 23 months. This is also becoming mainstreamed into the DHS; 3) The Food Consumption Score, which was developed by WFP (The United Nations World Food Program); and 4) The USDA Healthy Eating Index.

Approach Because this question is about drivers, it focused the group on what was already known or could be concluded from existing data to give further structure to a modeling effort – specifically the data needed to describe the spatial and socioeconomic patterns of dietary inadequacy in the US. Exploratory projects were designed for research with students over the summer and coming academic year. These include 1) Summarizing and visualizing data from the National Health and Nutrition Examination Survey (NHANES); Nielsen Scantrack, which tracks consumer purchases at grocery stores; the Whitehall II study data set, which tracks the influence of social status on health outcomes; and the USDA; 2) Extracting national heat maps representing particular indices from a nutrition database as a way to compare between potential nutrition indices and 3) Identifying data gaps.

Team 2: Robust transformative strategies for urban food production, healthy diets, and social capital.

Background. The magazine article *Urban farming is booming but what does it really yield?* [Royte2015] by Elizabeth Royte provides background and raises interesting issues about urban food production. The article questions "How far – and in what direction – can this trend go? What portion of a citys food can local farmers grow, at what price, and who will be privileged to eat it? And can such projects make a meaningful contribution to food security in an increasingly crowded world?" The article echoes group discussions during the workshop on the market inefficiency of urban food production, and to overcome this how much more valuable the urban food production and consumption experience has to be, in terms of personal preference, value-add and social capital, to become a self sustaining dynamic and meaningful share of the food consumption of the population.

Policy Level. Informing policy at a city level can be viewed as more tractable than at the national or global level. Strategies informed by model suggestions might be more easily implemented at the city level, and the effects might occur and be visible on a time-scale that enables verification of the modeling value. The topic also has enduring relevance given the greatest populations are urban and increasingly so.

System Description. Scales and levels present include individual, city and state government, personal and market economies, city and global environments, local and rural resources, low and high socioeconomic values. The group identified and discussed an interesting multi-scale and multi-level feedback dynamic that ran through urban food production, commercial and community food consumption experiences, market and personal price determinants, and individual choices and perceptions. Exogenous inputs included city governance policies on urban food regulations and promoting adoption, impact of environmental change on resources, global and national food production and markets, and urban demographic changes. It was conjectured that the behavior of the feedback dynamic determines whether urban food production can become self sustaining and gathered share, and, if so, what it would do to demographics, food prices and social infrastructure around food consumption. Alternatively time and income cost might outweigh behavioral willingness and social value and the urban food system would negative feedback into failure.

Approach. Modeling the feedback dynamic to understand its behavior, and the opportunity to enhance or dynamically control it, was of central interest to the group. What was particularly interesting, from the mathematical point of view, is its mix of 1) well understood physical or market processes that could be approximated by deterministic or stochastic functional relationships, 2) processes that are based upon individual or social behavior and choice, and 3) other processes for which the relationship between input and output would be uncertain because of difficulty in obtaining direct data, what the data itself could be confidently used to infer about the relationship, or because the chosen resolution of the model knowingly approximates, with error, underlying processes.

This led to an exciting cross-paradigm approach: coupling dynamical systems, agent based models and Bayesian modeling. For each question to inform, key outputs from the system would be related to a set of multiple criteria. Given a specification of functional relationships an overarching dynamical systems model would examine the feedback dynamic and track the time series output of the multiple criteria. This is the natural strength of dynamical systems. The difficulty is that the functional relationships must be prescribed. A background agent-based model would be called to calculate the result of behavior and choice processes, which would be difficult to prescribe otherwise. This is the natural strength of agent based modeling. The specifications themselves however are not certain, and the dynamics and answers of the model can change greatly with even small alteration in the functional relationships. To overcome this is a natural strength of Bayesian modeling. The result is a family of dynamical system models, each member of the family a possible specification of the functional relationships, with a posterior over the familys indexing set. This provides the opportunity to robust optimize interventions, or robust dynamic control, even if there is no well understood equilibria sets across the family of dynamical systems.

Team 3: How can (market) systems be designed and implemented so that food prices embody the social and environmental costs of food choices?

Background. Current prices of different foods do not accurately represent the social and environmental costs associated with consumption of those foods. For example, fatty and sugary foods lacking nutrients may be cheaper than nutritious foods though the social costs of obesity are high. Foods that have been produced, processed, packaged transported and retailed using unacceptable labour conditions may be cheaper than those with a fair food supply chain. The same may be true for environmental impacts across the food system. Given that food price is a major factor shaping consumption choices it is important that food prices accurately reflect social and environmental costs of food choices, as well as the economic costs.

System Description. There is no single actor responsible for fixing food prices, food prices are set by food markets. Accordingly, the question of how to ensure food prices embody social and environmental costs that are currently externalities is a question of market system design and implementation. This is a highly complex problem involving many types of actors at different scales and levels. Ultimately, food price for specific items is an emergent property of a complex and stochastic system. An exploration of the instruments available to various actors and their effects on food prices individually and in combination is necessary. Accordingly, the group felt that models used to address this question should be evolved together with food system stakeholders in an iterative collaborative framework involving participatory framing, model development, role playing, and simulation, testing, revision and further development.

Approach. The group began the process of developing an object-oriented meta-language for modeling the food system. This involves decomposing the food system, and its market dimensions, and developing an inventory of the physical, social, environmental, economic and political entities of the system and the links between them. For example, a list of actors and actions available to each actor, and an indication of what these actions act on etc. The relationships between these elements (the links) can be modeled in specific cases drawing on a library of mathematical functions. Ultimately, the aim is to develop an open-source software "application framework" for food systems research more broadly (see cross-cutting ideas, below).

In the context of the team's question, three case studies were identified: 1) Wine, because it has an elite customer base, representing an opportunity for the private sector to address the problem of externalities; 2) Corn, because it is a staple, representing an opportunity to look at policies that internalize costs at government level; and 3) Shrimp, which represents an example where externalities are geographically removed since shrimp comes predominantly from South East Asia. What can actors such as the US government, private sector and consumers do in this case?

Cross cutting themes:

While the specific questions focused each group on different aspects of the food system, clear cross-cutting themes emerged to help define a research agenda for the food systems modeling community.

Hybrid modeling. Temporal modeling, agent based modeling, and uncertainty modeling are each computationally intensive. Coupling them together with robust optimization or robust control solutions is an exciting mathematical challenge that cuts across applications in sustainability, climate, biology and medicine. The food system provides an unusually good framework in which to address this challenge, as the different levels of the system are all, theoretically, accessible, and there are many data sources, ranging from basic science to industry, market research and social media to tap into.

Data. Capturing the data and informing functional relationships requires connection and collaboration with food system scientists, urban social scientists and demographers, data and behavioral scientists, and agri-economists - underscoring the need for the community we are building. Data mining of urban food related terms from social media and smartphone apps to record real-time choices of volunteers relating to urban food could also be algorithmically mapped to agent structures.

On-line gaming for food systems modeling. One of the challenges in developing mathematical models of the food system is in understanding the logic of how human decision makers evaluate trade-offs under uncertainties in the complex situations and interactions that occur throughout the value chains of the food system. Traditional closed-form models of human behavior can over simplify and may be difficult to validate based on available historical data. One approach to overcoming these challenges would be the development of (massively multiplayer) on-line games to simulate a wide-variety of scenarios and to capture quantitative and qualitative choices made in context. The active learning environment of the on-line game approach could also provide validation for survey-based methods of garnering information from subject matter experts, and could be used as an education tool in a variety of settings.

Open-source software "application framework" for food systems research. The food system is a multi-scale system of complex systems which are intricately interwoven and interconnected. No single model of the food system will suffice for all research endeavors. As clearly demonstrated by the work in the three groups, the policy question being addressed is essential for shaping the model. Nevertheless, models addressing different questions do share some commonalities – for example, the structure and interactions defined in Figure 1.

An interesting, and potentially very useful, way forward would be to develop an application framework for computational food systems research that will reduce the time and effort spent re-discovering and re-inventing core concepts by providing a re-useable and extensible foundation and software templates for constructing computational models of the food system. Pre-existing code that is modular and componentized makes software development easier and enables researchers to better allocate their expertise to novel questions that will extending the state-of-the-art. Re-using code that has been previously tested can reduce errors and improve quality, as well as aiding in more rapid application development.

Domain-specific application frameworks have proven successful in a range of industries. An open-source approach to community development can facilitate a host of benefits including capturing successful patterns, architectures, components, and programming mechanisms so that researchers can more easily build on the best practices and fairly compare results as understanding in the field evolves [Lougee2003]

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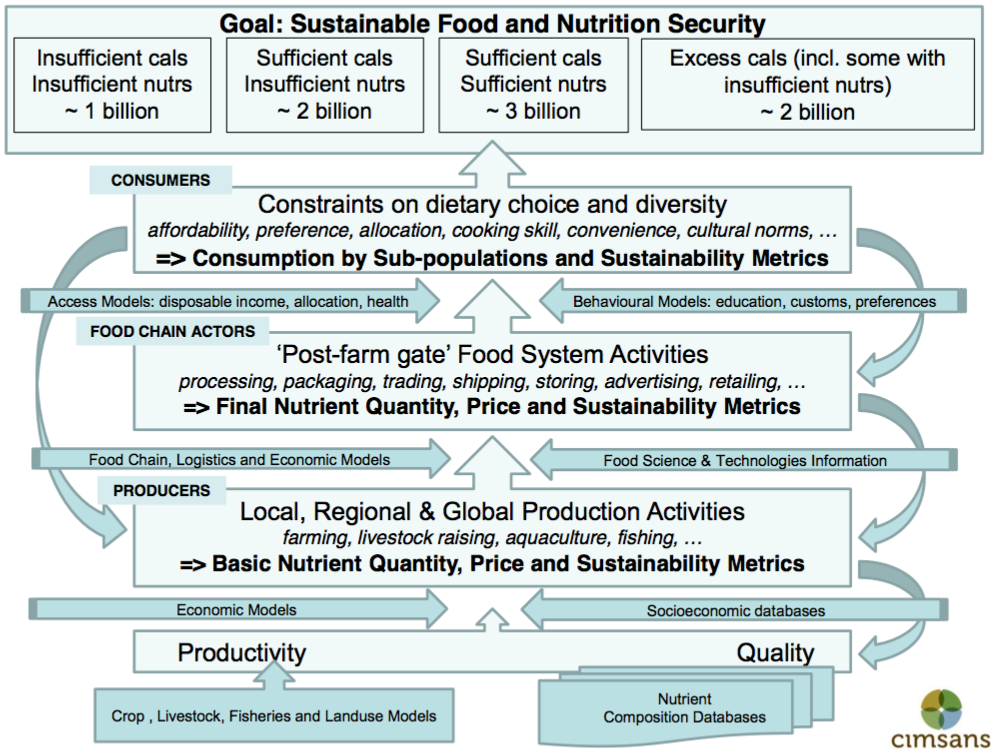

Figure 1. The Food System, reproduced from [1].

The top box represents food system *outcomes*. The pale blue *Consumers*, *Food Chain Actors* and *Producers* boxes represent food system *activities.* Dark blue boxes represent modeling approaches for separate components of the food system. Dark blue arrows represent inherent feedbacks.