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Assessing the impact of the global food system: Integrating models and statistics across agriculture, the environment, and human health*

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Abstract

Researchers have begun to integrate statistics and models to link dietary choices, the agricultural products farmers would need to produce to support different diets, and the environmental outcomes from alternative production technologies. The kinds of questions asked include the consequences of the worlds' population actually eating recommended diets, the implications of increasing organic production methods, and the consequences of increasing agricultural production on water use and water quality. The paper reviews conceptual models or frameworks that integrate food production, sustainability, and diet quality from an emerging literature on integrated agricultural systems. Recent publications include an interdisciplinary study from the U.S. National Academies, economic models that integrate environmental outcomes, and assessments of food systems published in nutrition journals. Results from an initiative at the Economic Research Service to model the impacts on production of alternative diets are also discussed. The conclusions identify gaps in existing data and strategies to capitalize on available information, including integrating agriculture statistics with statistics from other sectors.

Introduction

Food security ranks high on the global policy agenda. At present, over one-half billion people globally are food insecure. Looking forward, the world's population is projected to increase from 7 billion to approximately 9 billion by 2050, and per capita income is projected to grow in nearly all the world's regions. Agricultural productivity has grown in recent decades, but prospects for future growth depend on multiple factors including public and private research investments. Agriculture, as a major user of land and water, has an environmental footprint that produces positive benefits of open space, cultural landscapes, and wildlife habitat as well negative consequences including soil erosion and impaired water quality. Further, the health consequences of the global transition to more "western" diets and increases in obesity create another set of policy challenges. There are calls for a new food policy that takes into account these multiple goals.

Analysis of the global food system requires dealing with layers of complexity. One aspect of the complexity is the multiple nodes of decisions as the food system encompasses farmers, food processers, retailers, food service, and consumers. At each stage individuals and businesses make decisions about the use of resources based on preferences, income, profitability, availability and prices. In total these decisions have implications for the use of natural resources such as water and energy. A second dimension to the food system is the heterogeneity that exists across the globe. Land, water, and climate resources vary widely, including within countries and regions. Unlike a manufacturing process, the technology and use of inputs to produce agricultural products (e.g., rice or chickens) often differs by location. In addition, consumer preferences for food depend on cultural factors and income levels. A third aspect of complexity is potential for variability in production caused by weather. On a longer time scale, changes in climate are forecast to have differential effects on crops and livestock that will vary by region. Related to the nature of production, resources, and consumption, decisions made by farmers and consumers in one year affect future outcomes. For example, a farmer's decisions to adopt production practices that increase soil carbon have long, term future benefits. A consumer's choice of a healthy diet has positive, long-term health benefits.

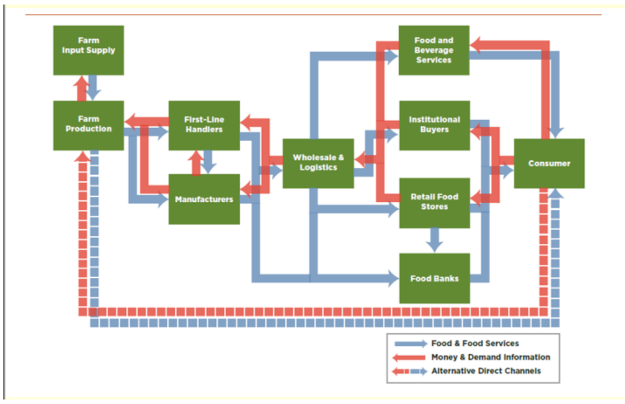
Agricultural and environmental economists, nutritionists, and environmental scientists have a long history of building conceptual and quantitative models to support public and private decisions. The models vary in scope from global markets to individual farmer. They have also traditionally focused on one or two aspects of an issue such as international trade policy, diet choices for humans or animals, or agricultural-environmental policy linkages. Over time, as computational power has grown, models have begun to look at multiple aspects of problems such as the linkages between international trade and environmental outcomes.

Perspectives on the food system

In recent years, researchers from multiple disciplines have undertaken analysis of different aspects of the food system. In addition, national governments, private industry, and international organizations have invested in developing models of food systems. Each approach shares common aspects and four are reviewed to provide a flavor for factors considered and data requirements.

Figure 1 provides a schematic of a food system from a recent report of the U.S. National Academies, “A Framework for Assessing Effects of the Food System.” The flows of money and demand information start from the consumer and work through retailers and manufacturers to farmers. In a wealthy, developed country such as the United States, consumer demand plays a large role in outcomes as the food system adapts to meet needs for convenience or variety. For example, in 2013, food away from home accounted for 49.6 percent of Americans’ food expenditures. In 1960 the share was 23 percent. The rise in spending for food away from home reflects the growth in two-earner households that value convenience and the average incomes of Americans where food accounts for 10 percent of income. Consumers in developed countries such as the United States are not limited by farm production from their region or nation as shipment of food takes place across regions and imports provide products that are not produced domestically or meet demand for specific goods.

Figure 1. Conceptual model of a food supply

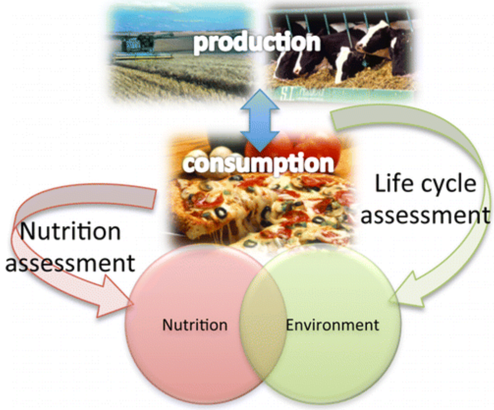


Elements or actors in this supply chain in one area (e.g., region or country also have interactions (e.g., international trade) with actors in other areas.
Source: *A Framework for Assessing Effects of the Food System*, National Academies of Science.

The National Academies framework explicitly shows how money moves across the system. The size of the financial flows plays a role in determining the influence of different components. To illustrate with statistics from the United States, for a typical dollar spent in 2012 by U.S. consumers on domestically produced food, including both grocery store and eating out purchases, 31.1 cents went to pay for services provided by foodservice establishments, 15.8 cents to food processors, and 13 cents to food retailers. At 5.6 cents, energy costs per food dollar are up 27 percent since 2009, but still below the 6.8 cents that energy costs contributed in 2008. (Source: ERS, USDA Food Dollar)

The second perspective focuses on the links between production and consumption and estimates the implications for nutrition and the environment. Heller et al acknowledge the “vast and interconnected array of physical, social, and political systems, known collectively as the ‘food system’”. They discuss three policy options to improve food system performance. One is for consumers to constrain demand, especially of foods with high environmental impact. A second is to produce food more efficiently. A third, called food system transformation, takes a broader view and looks for opportunities to improve performance across the entire system. Heller et al discuss the Life Cycle Assessment (LCA) tool to assess environmental impacts of product systems and services. The authors expand this approach to add a component on nutrition and food consumption (Figure 2).

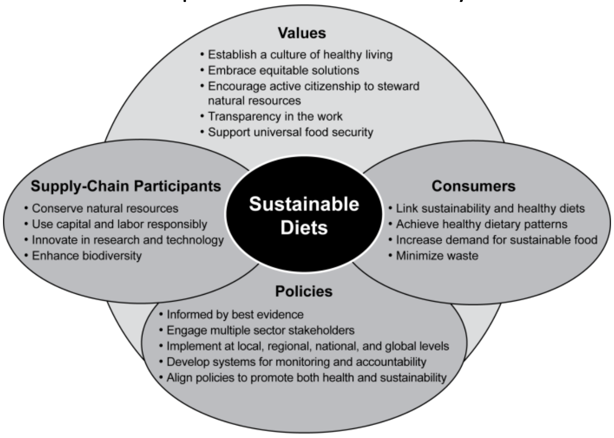
Figure 2. Food consumption-oriented environmental impact assessment (Source : Heller et al)



The term sustainable diets is used to describe food consumption that is consistent with sustainable food production (e.g., implications for land use, water quality, biodiversity) and consumption (e.g., food waste). A few national governments have begun to incorporate sustainability into dietary guidelines that recommend healthy food choices (Health Council of the Netherlands, 2011; Ministry of Health Brazil, 2014). As part of a review of the scientific literature to inform the U.S. Dietary Guidelines (2015), an expert panel examined the state of knowledge around sustainable diets which are defined as a pattern of eating that promotes health and well-being and provides food security for the present population while sustaining human and natural resources for future generations. Whether or not to incorporate sustainability into the forthcoming Dietary Guidelines ignited controversy. The parts of the Government responsible for the decision have decided not to incorporate sustainability because it is outside the scope of the guidelines mandate to provide nutritional information (USDA, 2015).

Figure 3, from the panel's report, illustrates four aspects—values, policies, supply-chain participants, consumers—that shape whether consumer decisions lead to sustainable diets. Notably, the schematic points to the role of incentives as the choices by consumers, producers, and policy makers shape the final outcome. A second take-away from the image is the connections between all parts of the food system.

Figure 3. Drivers of Sustainable Diets
(Source: Scientific Report of the 2015 Dietary Guidelines Panel)



Johnston et al adapt a framework from FAO to characterize sustainable diets (Figure 4). Under this model, the components in the large green ovals affect the ability to achieve sustainable diets. They represent aspects of the three pillars of sustainable development: social, economic, and environment. Each component relates to and influences the other dimensions. Within each green oval, Johnston lists the factors and processes that constitute the influence of that component to achieving a sustainable diet. This model illustrates the large number of potential influences on sustainable diets. In order to test hypotheses about the influence of each component, data on the levels of each factor and model for the processes are needed. Additional data and models are required to assess the links across each green oval or component.

Figure 4. Model of Sustainable Diets
(Source: Jessica L. Johnston et al. Adv Nutr 2014; 5:418-429)

Quantifying an integrated food system

To inform growing policy interest in an integrated food system, researchers from multiple disciplines are developing models to quantify the links between food consumption and production. The complexity of agricultural systems has inevitably led researchers to make simplifying assumptions about one or more aspects of the food system to forecast future changes in markets from exogenous changes such as climate or policies. These assumptions allow for drilling into the effects of fewer aspects of the problem in order to provide in-depth analysis. For example, in order to assess the effects of changes in farming practices on water quality, researchers require detailed information about regional soil conditions and current farming practices, but need to make simplifying assumptions about the effects of policy changes on national or global market conditions. The growing interest in the linkages between components of global food systems, has led to the development of integrated, global models. While these models incorporate linkages across different parts of the food system, they are not able to include the heterogeneity and variability of farming systems across the globe.

Multiple approaches have emerged to quantify the relationships across the food system. Eshel et al characterize current models as top down versus bottom up: “Current work in the rapidly burgeoning field of diet and agricultural sustainability falls mostly into two complementary approaches. The first is bottom–up, applying rigorous life cycle assessment (LCA) methods to food production chains. …The second agricultural sustainability research thrust, … is a top–down analysis of national or global production statistics.”

As with all models, there choice of model depends on the questions being asked and available information. Table 1 sorts the different approaches following the top down and bottom up lens. The last rows of the table provide examples of “bottom-up” studies that include Life-Cycle Analyses (LCAs). They consider one or at most a handful of farms at a time. Because of wide differences due to geography, year-to-year fluctuations, and agro-technological practice, numerous LCAs are required before robust national statistics emerge. Another challenge is that the underlying data may come from different analytical and statistical approaches.

LCA's pose additional conceptual challenges in drawing boundaries around the product that is analyzed. For example, a study of corn use for ethanol production needs to determine the geographic boundary of production (local area for ethanol plant or global production implications of associated price changes) and linkages to other uses of corn (decreases in livestock use would offset increases in ethanol use). Traditional LCAs have not taken the market consequences of production into account. Moving in this direction, calls for merging bottom up with top down modeling.

Top down models focus on the food and agricultural sector in isolation (partial equilibrium or simulation models) or the economy as a whole (general equilibrium). Both agriculture sector and economy-wide models vary in geographical detail, but have the strength of representing average values. The models take advantage of international, national, and regional statistics to calibrate a model that can be used to analyze alternative scenarios. The key challenge with this approach is obtaining defensible numerical values and uncertainty ranges for large number of parameters needed in the calculations. These parameters include physical production relationships (animal feed conversion rates), current and future diets.

Tillman et al project global demand for crop production in 2050 using a top down model that also estimates the environmental impacts. Their analysis forecasts crop demand by making assumptions about income growth and the relationship to per capita calorie and protein demand. The model decomposes consumers by income groups to produce a more refined analysis. On the supply side, Tillman et al quantify the relationship between yield, inputs and climate. The model estimates changes in land clearing, GHG emissions and nitrogen fertilization. The model is adapted to simulate alternative production technologies. Behind the model is a series of statistical analyses to estimate relationships between different factors including nitrogen fertilization intensity and caloric yields. However, the authors make clear that causal relationships are not estimated. They also caveat their analysis by stating that the pathways are not necessarily attainable or feasible.

The IFPRI and Economic Research Service (ERS) of the U.S. Department of Agriculture (USDA) models ask similar questions about how alternative diets affect market prices and production. For the U.S., if Americans transitioned to the diet recommended by the Federal government, it would be a major change that would reduce consumption of fats, sweets and animal based protein to more fruits and vegetables. Given the magnitude of the dietary changes, the ability of the food system to adjust will impact the feasibility and the cost of any changes. The ERS research program sequentially links three separate models for diet, agricultural production and environmental outcomes, and the food distribution system to assess the impact of the dietary changes (Figure 5). The IFPRI paper takes a similar approach by estimating the changes implied by alternative diets and applying these to a global model of agricultural consumption, production and trade. These two approaches have strengths in using models of the agricultural system that impose economic relationships to ensure that the outcomes align incentives for producers and consumers through markets. As such, the models solve for prices under alternative scenarios which provides information on the distribution of changes.

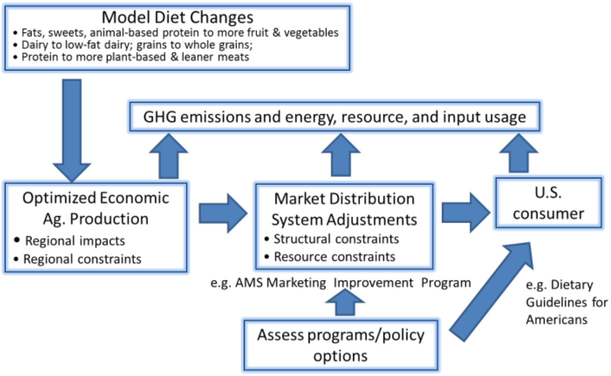


Figure 5. Economic Research Service, USDA linked models to assess dietary changes

The Center for Integrated Modeling of Sustainable Agriculture and Nutrition Security (CIMSANS) has launched an initiative assess nutrition, food, and environment linkages. The initiative is building partnerships between academia, government entities, and the private sector to build a comprehensive, globally-integrated model-based assessment of how food (and especially its nutrient content) is produced, processed, wasted and consumed. CIMSANS' planned framework has many similar elements to the one that ERS is building. While the initial models will likely connect through sequential linkages, the ultimate goal is to have an integrated, simultaneous system.

Table 1. Types of models

Questions	**References**	**Type of model**	**Assumed constant**	**Adjusts**
How do alternative diets affect market prices and production?	Msangi & Rosegrant (IFPRI)	Partial equilibrium	New diet composition	Global prices, consumption, nutrition status
What are the implications for agricultural production and environmental outcomes of consuming recommended diets?	ERS, USDA	Partial equilibrium linked models	Global markets	Food consumption, production, land and other input use
What are the implications of global consumption of alternative diets? How do changes in ag productivity, waste, international trade affect outcomes?	Tillman & Clark	Partial equilibrium model	GHG emissions from LCA models	
How is food (including nutrient content) produced, processed, wasted and consumed? What role does food play in sustainable nutrition security?	Acharya et al;	Linked models	Conceptual paper with modeling framework to support integrated assessment of consumer food choices, production, and policies.	
What diet meets nutritional requirements and minimizes one or more environmental indicators (e.g, GHG)?	Livewell; Eshel et al; Johnston et al;	Linear pro-gramming	Prices	Foods consumed
What are the resources consumed (GHG, water) in the production of specific agricultural products, nutritional aspects of food, or consumption of diets?	Heller et al;	Life Cycle Analysis (LCA)	Prices, quantity produced	Estimates resource use associated with production of specific product or cons. of basket of goods. Definitions are important.

Data needs

All the quantitative models of food systems require data for a large number of variables on food production, environmental effects of production, and food consumption. Various data sources provide this information at different levels of aggregation. The modeling teams have developed approaches to match and link data. However, there is a need for more work by data producers to improve linkages across data systems and to fill in data gaps. The UK Livewell study makes the point that, “Future work related to diet and sustainability needs to consider how best to combine and harmonize datasets which have been set up for different purposes – for example GHGE data for the production of food commodities and dietary intake data based on food as consumed. The difference in the way the food is reported can influence the perception of the impact it is having on the pre-RDC GHGE. For example, a kilogram of uncooked rice has a pre-RDC GHG value of 3.50 kgCO2e, but is equivalent to approximately 2.7kg of cooked rice once hydrated.”

The work by ERS considers the components of the food system and draws on national accounts data to measure the inputs used at different places in the system. The United Nations’ National economic accounting guidelines recommend the use of input-output (IO) material flow studies as a best practice for achieving “a consistent analysis of the contribution of the environment to the economy and the impact of the economy on the environment.” The ERS framework examines how energy and water are used throughout the U.S. food system. A challenge is the treatment of wholesale and retail trade as generic industries serving all wholesale and retail transactions leads to an under reporting of food-related energy use by the trade services.

The kinds of data used across the models point to areas where the quality of data has a strong influence on the results and policy implications. Table 2 lists major data sources for selected studies. Across all the models, basic information on core agricultural production statistics and the use of inputs serve as the foundation for top down analyses. Information on the consumption of food is also an input into many models. These are two areas that need improvement, especially in developing countries. Another key variable in the models is the past and future growth in yields and agricultural productivity by region. Measurement of yields and productivity growth depends on basic agricultural production and input use data; further reinforcing the importance of basic agricultural statistics.

The UN Global Strategy for Agricultural and Rural Statistics (Global Strategy) is working to strengthen capacity to produce sectoral statistics. The Global Strategy has defined a core, minimum set of data that encompasses a large part of the data necessary to build global models. A second pillar of the global strategy is to integrate agricultural statistics into the broader statistical system. The development of food system models creates a new demand for integrated data.

Table 2. Data needs for selected empirical models

Study	**Model type**	**Data used (selected)**
Tillman et al	Global, ag sector simulation	FAOSTAT ; SAGE (location specific cropland ; UN population ; IPPC
Tillman and Clark	Global, ag sector simulation	USDA Nutrient Database, Total Economy Database, FAO FishStat, 120 published LCAs
Heller et al	LCA	USDA, ERS food availability, food loss. USDA agricultural production
Eshel	Ag sector simulation	USDA agricultural production data

Conclusions and future challenges

Food and agriculture touch all people and a large portion of the world’s land and water resources. The conceptual frameworks for sustainable nutrition develop the linkages between the range of economic, social and environmental factors that potentially affect dietary choices and environmental outcomes. The frameworks provide different perspectives. The National Academies and Heller frameworks trace the linkages between the different parts of the food system from producer to consumer. The U.S. Dietary Guidelines and Johnston conceptual models portray the links between the factors driving different outcomes.

In the past five years, research teams have developed quantitative models of the food system that can be broadly characterized as top down or bottom up. The top down models draw on FAO and national data systems that provide consistent information for a large number of variables. The bottom up models start from detailed LCAs to characterize relationships across the supply chain. Each approach relies on assumptions to aggregate, disaggregate or distribute data by income level or environmental conditions. Each approach has strengths and weaknesses in terms, many that can be linked to data availability, aggregation, and the boundaries of the study.

The current set of models has produced some common results that authors believe can inform policies. For example, the several models rank the environmental impact of food products. They generally find that that plant based diets are more sustainable. They use fewer resources because grains and oilseeds are not converted to meat; although local production conditions make a difference. Another common finding is that raising agricultural productivity leads to less pressure on resources especially land. These findings point to the potential benefits from linking dietary choices and nutritional outcomes to agricultural production and the food system.

The model frameworks by the National Academies, ERS, and CIMSANS include economic activity and resource use between the farm gate and food consumption. Given the large share of food expenditures on processed food or food consumed away from home, nutritional outcomes and the environmental footprint of food depend on having a detailed model of this part of the food chain. Building models of the post-farm gate requires data and parameters that link agriculture to other parts of the economy and come from statistics on national accounts. Understanding implications for GHGs and other resources requires information about specific supply chains.

The current state of models that link health, nutrition, agricultural production, and environmental outcomes represents the early stages of development. A comparison of modeling frameworks, empirical models, and data used points to areas for future investment in statistics. In addition, this overview provides a set of questions that users of the quantitative results need to ask before drawing policy conclusions. These include: What is the level of aggregation of products and geography and can meaningful results be derived at this scale? What are the boundaries of the study (does it allow for substitution in production and consumption)? Does the model allow for incentives to affect decisions by producers and consumers (e.g., does it represent an equilibrium)? What is the source and quality of the underlying data? As this field of research develops, new investments in basic data and additional studies will add to the set of findings around linkages across the food system. Further developments in modeling systems will provide the capacity to explore the effects across the food system of a range of policy options.

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