A systems science perspective and transdisciplinary models for food and nutrition security

Ross A. Hammond[a,1] **and Laurette Dubé**[b]

[a]*Center on Social Dynamics and Policy, The Brookings Institution, Washington, DC 20036; and* [b]*McGill World Platform for Health and Economic Convergence, McGill University, Montreal, QC, Canada H3A 1G5*

Edited by Prabhu Pingali, Bill and Melinda Gates Foundation, Seattle, WA, and approved March 30, 2012 (received for review June 10, 2011)

We argue that food and nutrition security is driven by complex underlying systems and that both research and policy in this area would benefit from a systems approach. We present a framework for such an approach, examine key underlying systems, and identify transdisciplinary modeling tools that may prove especially useful.

complexity | agri-food | health | disease | environment

Nutrition is a fundamental human need, affecting health and well-being throughout the lifespan in myriad ways. A central concept in the study of human nutrition is food and nutrition security, which is typically defined as "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (1). The absence of food and nutrition security can have significant consequences for individuals and for society, including malnutrition, obesity, disease, and poverty.

Despite rapid growth in agricultural production over the past four decades, significant malnutrition persists. Average per-capita food consumption was below the recommended 2,200 kcal/d in 33 countries in 2003. Globally, more than 850 million people lack adequate access to food on a regular basis, with a third of these in East and Southeast Asia, another third in South Asia, and a quarter in sub-Saharan Africa. In sub-Saharan Africa, one of the most food-insecure regions, the number of hungry people has gone up by 20% since 1990; more than a third of the population is undernourished in such countries as Kenya and Tanzania. There are 126 million underweight children in the world and over 2 billion people who suffer from micronutrient deficiency (2–4).

At the same time, there has been an alarming rise in obesity in the developed world (5, 6) and, increasingly, in the developing world as well (7–9). The obesity rate in the United States doubled between 1970 and 2000, to almost 30% (5); worldwide, nearly 1.5 billion people are now overweight or obese (9). Like malnutrition, obesity has significant implications for public health (10, 11) and health care costs (12). Obesity can coexist in the same populations as malnutrition, and it may be linked to the same forces that drive reductions in malnutrition (13, 14).

Complexity of Food and Nutrition Security

Both phenomena, malnutrition and obesity, are manifestations of widespread food and nutrition insecurity. The determinants of this insecurity are complex. A primary driver of food security or insecurity is the agricultural food system. The agri-food system spans a series of interrelated processes, including production of raw food materials through farming and raising of livestock, processing and packaging for consumption, distribution, and utilization by consumers (15). These processes are affected by a range of influences, including diffusion of agricultural technology (16, 17), functioning of capital markets, infrastructure at both local and regional/global levels, organization of firms and supply chains, sociopolitical factors governing food practice and land ownership (18), and social norms and cultural preferences (19). The overall food system crosses multiple levels of scale, from individual farmers and consumer decision makers to national and international economic markets, multinational firms, and global supply chains, and its structure changes over the course of economic development.

Food and nutrition security is also strongly shaped by systems outside of the agri-food sector. Even given adequate supply and access to food, nutrition security can be influenced by individual heterogeneity in physiology or disease (20, 21) and by access to clean water, hygiene, and cooking practices (22, 23). Evidence suggests that malnutrition can be affected by infectious disease, and, in turn, undernutrition (and potentially overnutrition) can shape susceptibility, transmission, and progression of infection, creating reinforcing feedbacks (2, 13, 20, 24–28).

Food and nutrition insecurity in the future is likely to be affected by ongoing regional and global trends that have an impact on the potential functioning of the food system, such as climate change (29–35), population growth (3, 36), economic development (37, 38), urbanization (36, 38, 39), migration (38, 39), and especially environmental and ecosystem dynamics (36, 40–45). These constitute distinct dynamic systems that interact with food production, distribution, or consumption, and affect the stability and sustainability of the food supply and of nutrition itself.*

The complexity of these underlying systems makes food and nutrition security a particularly challenging topic for scientific study. The processes and influences described above not only cross a wide range of levels of scale, but are also the province of very different fields of science (economics and business, epidemiology and immunology, ecology and climatology), each with its own terminology, techniques, and forms of data and modeling. Yet interactions across and between levels and systems are critical drivers of ultimate dynamics of food and nutrition security. This type of dynamic complexity† makes policy making, governance design, and evaluation especially challenging (47, 48), because changes in one process or at one level may be offset (or even reversed) by adaptive responses elsewhere in the system. Similarly, potential synergies and feedbacks between components that could be harnessed for policy impact might go overlooked. Despite promising efforts

---

Author contributions: R.A.H. and L.D. performed research and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1] To whom correspondence should be addressed. E-mail: rhammond@brookings.edu.

*An alternative definition of food and nutrition security reflects both the importance of sustainability through time and the household level of scale (rather than population level): "A household is food secure when it has access to the food needed for a healthy life for all its members (adequate in terms of quality, quantity, safety, and cultural acceptability), and when it is not at undue risk of losing such access" (46).

†The term "dynamic complexity" denotes the counterintuitive dynamics that can result even from relatively simple systems due to nonlinearity, interaction of system elements, and feedback loops.

www.pnas.org/cgi/doi/10.1073/pnas.0913003109

toward development convergence, agri-food, health, and environmental systems are still largely studied and administered with little direct attention to linkages between them (35, 45). Global development initiatives remain poorly connected with regional, national, and community-level efforts, missing potential synergies.

These challenges suggest that a systems approach may be of particular value in understanding and shaping food and nutrition security. Such an approach would connect interrelated systems across disciplinary lines, and explicitly examine interaction effects and feedbacks. Since the design, management, and control of complex adaptive systems can involve a challenging array of distributed and interacting agents, powerful feedback loops, large time delays, and counterintuitive system behavior, this may require innovative methodological strategies. Modeling techniques drawn from complexity science have arisen to address such challenges, and have proved to be of particular value in the study and management of other similarly complex problems. Their application to food and nutrition security can provide fresh insights into the interconnectedness and interdependencies within as well as across sectors, scale, space, time, and jurisdiction, potentially identifying promising new strategies for single and/or system-level intervention. Of particular interest for a systems approach to food and nutrition security are system dynamics (SD) and agent-based modeling (ABM) (47–55).

In the remainder of this paper, we first present a framework for an initial systems approach to food and nutrition security. This framework identifies key feedbacks and links between important system components, focusing on the agri-food, health, and environmental systems. We then examine each of these three systems in more detail. Drawing on relevant theoretical and empirical literature, we identify key components of and trends in the food system itself that play an important role in food and nutrition security at different levels of economic development. These would form basic building blocks for systems modeling. Next, we highlight two especially important drivers of food and nutrition security that lie outside of the food system itself: disease and environment. We explore in more detail the evidence for key feedback loops and linkages between these systems and food and nutrition security, and identify existing models and frameworks from both epidemiology and environmental science that could serve as starting points for a broader systems model of food and nutrition security. Where relevant, we identify particular modeling techniques that may prove especially advantageous. Finally, we conclude by reviewing the potential and the challenges of a systems approach and transdisciplinary models for food and nutrition security in the 21st century.

Systems Framework for Food and Nutrition Security

In Fig. 1, we outline a framework for the study of food and nutrition security focused on three major systems: the agri-food system, the environmental system, and the health/disease system. All three represent key drivers of food and nutrition security, and each independently has a strong mathematical or systems modeling literature. However, many of the most important links and feedbacks between

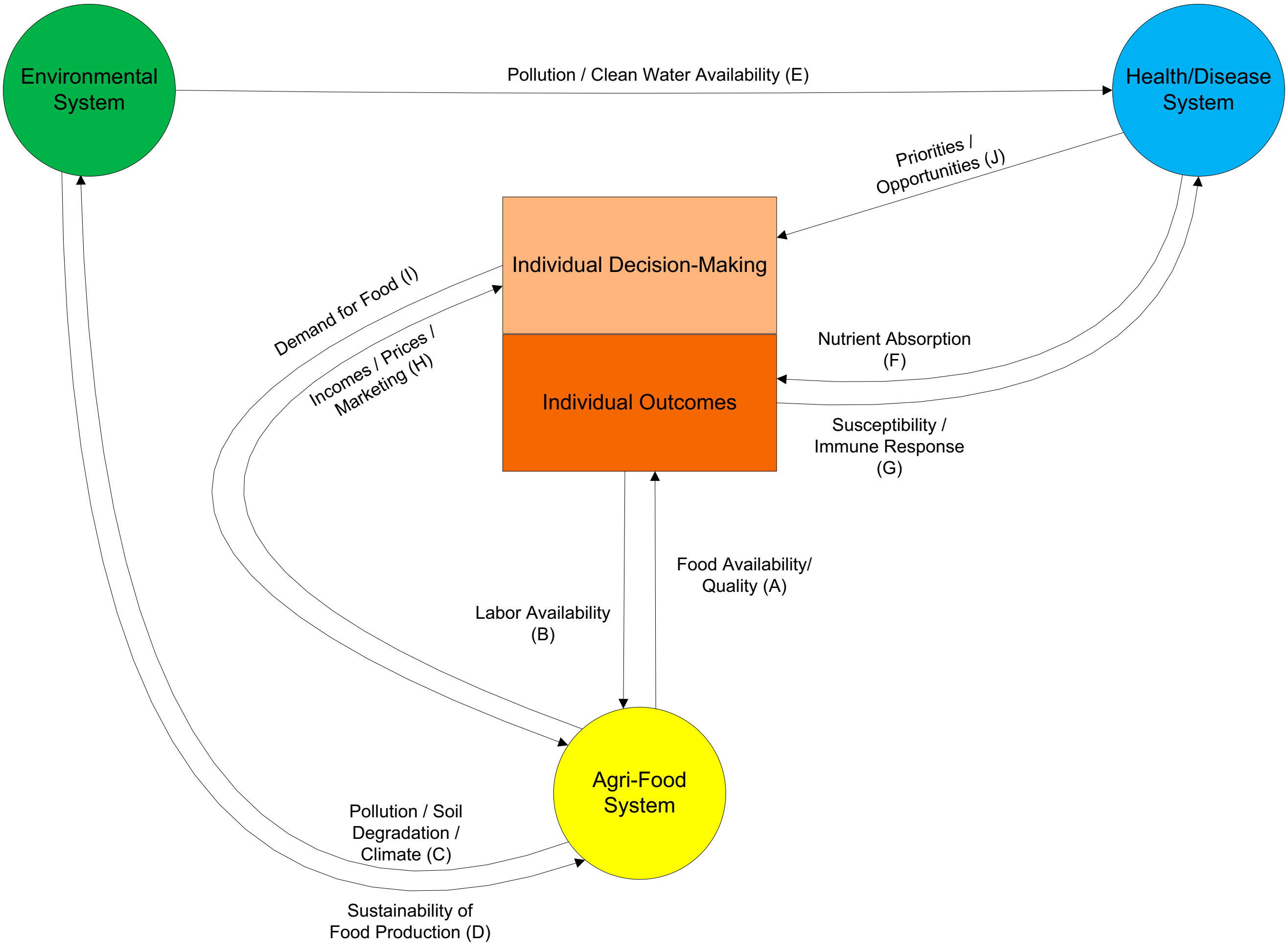

Fig. 1. A systems framework for food and nutrition security.

these systems and food and nutrition security have not been extensively modeled, despite growing empirical evidence of their importance. Here, we identify and briefly discuss 10 key links and several feedback loops[‡] they form between the three systems and food and nutrition security. In the subsequent sections, we summarize existing empirical evidence and modeling work on these systems and links, and identify ways in which new methodologies might contribute.

Our framework is organized around two loci of influence on food and nutrition security: influence on outcomes via individual decision making (about what to buy, what to eat, and what to prioritize) and influence on individual outcomes irrespective of decision making (e.g., health status, food availability).

The agri-food system affects the individual in two major ways. First, agri-food production and distribution systems shape the quantity and nutritional quality of food available to individuals at a given place and time, thus affecting individual outcomes (Fig. 1*A*). Second, agri-food systems influence individual decision making through several interrelated channels, such as food prices, advertising, and marketing, and by providing income through employment of farmers or laborers (Fig. 1*H*). Both individual decision making and outcomes, in turn, affect the agri-food system itself. The availability of a healthy and productive workforce (to produce and distribute food) is strongly shaped by worker health and nutrition outcomes (Fig. 1*B*). Similarly, the demand curve faced by agri-food production is made up of the aggregation of individual decision making in response to price and quantity (Fig. 1*I*). Identifying these links helps to bring important feedback loops into view. For example, poor food availability can lead to malnourished and unhealthy workers, which can decrease production and further limit availability of food.

The health and disease system also affects the individual via several pathways. First, regardless of decision making and food intake, health status can affect actual absorption of nutrients (and thus outcomes) (Fig. 1*F*). Second, health status can affect individual decision making by shaping available employment opportunities and income, changing relative priorities (and spending), or constraining the feasible choice set for both economic and food decisions (Fig. 1*J*). Individual nutrition outcomes feed back to affect health because individual susceptibility to infection or progression and transmission of disease can be altered by nutrition status (Fig. 1*G*). This can produce a feedback loop in which poor nutrition can lead to poor health, which makes adequate nutrition still more difficult.

Both the agri-food system and health and disease system interact with a third system, the environment, in ways that have important downstream impacts on individual food and nutrition security. Ecosystem health can affect human health via the presence of pollutants or toxins and the availability of clean water for human use (Fig. 1*E*). Both ecosystems and climate also have an impact on the agri-food system by affecting the sustainability of food production levels and methods, the availability of water for irrigation, and soil fertility (Fig. 1*D*). In return, the agri-food system can have an impact on ecosystems and climate via pollutants and soil degradation associated with intensive farming, via the water cycle, and via emissions of greenhouse gases and elimination of carbon reservoirs (Fig. 1*C*). This defines another feedback loop: Increasing demand for food and limited cultivable land can lead to unsustainable farming practices, which increase pollutants and erosion while decreasing soil fertility, leading to even more pressure on agricultural production.

We argue below that implementing a rich, multisystem model of food and nutrition security that captures these links may require mathematical and computational techniques from complexity science, such as SD and ABM. These have been widely used elsewhere in the recent scientific literature, and indeed within many of the individual scientific disciplines covered here (49–71). In addition to facilitating integrated modeling of food and nutrition security across the agri-food, health, and environmental systems, these techniques have the potential to generate new insights into each system individually. This potential comes from the ability of systems modeling to effectively capture feedback, individual and spatial heterogeneity, nonlinear dynamics, multilevel and spatial interaction, and adaptation—features that are central to all three systems.

Agri-food System

The agri-food system is a central driver of food and nutrition security, affecting individual opportunities, decision making, and outcomes (Fig. 1). The structure and dynamics of agribusiness (food production, distribution, and marketing) are strongly shaped by the trajectory of a country's economic growth. Development is generally characterized by a falling share of agriculture in economic output, rising share of urban population compared with rural population, and rising economic activity in industry (72, 73), along with restructuring of the modes of agricultural production and the labor force (74–76). The role played by agribusiness in food and nutrition security is therefore changing across different stages of economic development. Models of food and nutrition security will provide the richest insight if they capture the complexity and heterogeneity of this structural development transition. However, much existing modeling of agribusiness and the agri-food sector in developing economies does not fully include these dynamics (77).

One reason for this limitation may be methodological. Predominant forms of mathematical modeling of the agri-food sector [e.g., macroeconomic general equilibrium (GE) approaches] offer many insights, but are not well-suited for modeling some of the turbulent dynamics of economic development because they are generally predicated on underlying assumptions that exclude nonequilibrium dynamics, multiple levels and forms of interaction between actors, inefficient financial markets, deviations from rational expectations, or incremental adaptation. Techniques from systems science, such as SD or ABM, may allow richer representation of these complex, dynamic, and adaptive processes involved in the agri-food system during the transition from early to late stages of development.

For example, development in the agri-food system is characterized by changes in institutional structure as people aggregate into communities, cooperatives, firms, supply chains, distribution networks, and distributed markets. GE models abstract away these complex structures and modes of interaction between actors, generally assuming interactions occur only through prices and between "representative agents" (identical farmers, traders, firms, or households). By contrast, techniques such as ABM can incorporate rich patterns of interaction by explicitly modeling each individual and networks of links with others, allowing for individual behavior altered by learning, imitation, or local social influences. In such a model, agents can migrate, aggregate into institutional structures like banks and firms, and display enormous heterogeneity in their information sets and behavior. ABMs can also capture "network-based" processes critical to villages, communities, and supply chain participants; can model phenomena, such as "herding," which may drive spikes in food prices (78); and can incorporate findings from behavioral economics that challenge conventional "strong" rationality assumptions. This facilitates more nuanced modeling of how expectations, risk perception, and labor/investment decisions are made over the course of development.

[‡] A feedback loop denotes a causal chain, wherein a change in one part of the system affects another component, which, in turn, affects the original component.

Complex systems modeling approaches also allow consideration of rich dynamic pathways. In many macroeconomic models, price signals are immediately integrated into an individual's decisions; however, in developing economies, such signals may operate on a diverse set of temporal, geographic, and administrative scales, often with substantial asymmetries. The transition from subsistence agriculture to industrial food production arises from the progressive accumulation of small, subtle individual adaptations and market transformations. Better understanding of these dynamics, facilitated by systems models, may prove important for identifying novel pathways for economic convergence and smallholder food and nutrition security. Similarly, traditional microeconomic and macroeconomic models that allow for only minor fluctuations around stable equilibria have limited applicability to unstable periods of agricultural and industrial development. ABM and SD can relax assumptions of efficient financial markets to study feedback mechanisms that amplify small effects (e.g., progressive changes in the nutritional quality of agricultural and food stocks and their consequence for nutrition and health transitions).

Agricultural development is also embedded in a broader social and cultural context. The propensity (and ability) to eat nutritious foods and maintain a healthy diet can be affected by social norms, socioeconomics, and power structures tied to land ownership and social status. As a result, different segments of society may vary widely in the type and quantity of food they find available, affordable, and culturally acceptable (18). In addition, recognition of feedback between the agri-food sector and other systems, such as health and environment (below), can be critical for effective policy design. Indeed, such feedbacks may help to explain how efforts to reduce undernutrition in developing countries can have the double-edged effect of increasing levels of obesity in those same countries (79). Computational systems models can help to explicitly include both the heterogeneity and the feedback loops that result from the broader context in which agriculture functions.

The impact of agri-food systems on food and nutrition security, and on other sectors, varies by development stage (18), as do the most important actors and processes, introducing additional complexity. In the early stages of development, key actors are governments, development agencies, and smallholders; private sector involvement is typically limited. Farmers at this stage primarily tend small plots in marginal environments, using a variety of indigenous agricultural methods that have emerged as the most adaptive over centuries of biological evolution (80). As development takes place, private ownership and management of natural resources grow in relative importance, replacing the communal control and open access that predominate in early stages. This has important implications for stewardship of environmental and ecosystem resources (*Environmental System*) and sustainability (81, 82). As development proceeds, domestic conglomerates form, trade and foreign direct investment expand, and transnational food manufacturing and supermarkets linked into global value chains enter the market (83). Increasingly complex supply chains and economic networks tie farming production, processing, and marketing together (often unevenly) across markets and jurisdictions. With this process of development comes increasing pressure on the economic well-being (and nutrition security) of smallholders, who are often at a disadvantage compared with larger commercial farmers capable of supplying larger volumes of quality-assured products with more bargaining power and better access to information, services, technology, and capital (84). In addition, this process has implications for diet composition and health, with a transition from fresh and minimally processed food to highly processed food and from domestic local supply to multinational concentrated supply (85–87). This shift may be associated with growing rates of obesity in many developing countries undergoing a nutrition transition (88).

This dynamic complexity implies that a sufficiently rich model of the agri-food sector must have three particular characteristics: flexibility to capture changing patterns of interactions through time tied to stages of development; inclusion of sufficient heterogeneity of individuals and modes of interaction; and capacity to include links to (and feedbacks with) other sectors, such as health and environment. We argue that systems approaches are especially well suited for these requirements. They offer the potential to provide a deeper analytical understanding of the dynamics ultimately driving the food and nutrition of individuals and populations (77). They may also allow examination of development pathways with more optimal short-term and long-term net impact on nutrition, including Webb and Block's strategy for reducing malnutrition without producing obesity as an adverse side effect (89).

Health and Disease System

The relationship between nutrition and disease is complex and bidirectional. Many infectious diseases can directly lead to malnourishment, even when access to food is sufficient (2, 20, 26) (Fig. 1*E*). At the same time, malnourished (and overnourished obese) individuals are more susceptible to many diseases (26, 27, 90–92) (Fig. 1*G*).

Malnutrition is often described as "the most important risk factor" for illness and mortality globally, and it is directly or indirectly responsible for more than half of all deaths in children under 5 y of age (2, 27). Birth weight is the most important single predictor of early childhood mortality (23). Much of the impact of malnutrition on mortality and morbidity may operate indirectly through infectious disease.

Adequate nutrition is essential for activation and proper functioning of the immune system (26, 27). Malnutrition can affect both individual susceptibility to infection and the course of diseases in an infected host via several distinct mechanisms and pathways, including compromised immune activation and function, reduced epithelial integrity, altered microbiome, diminished treatment response, greater risk for comorbidities, and oxidative stress (13, 26–28, 91, 92). Indeed, much of the mortality generally attributed to infectious diseases may driven by a combination of infection and malnutrition (27, 92). For children under 5 y of age, being underweight or undernourished accounts for more than half of the mortality risk from the most prevalent infectious diseases (2, 23, 27, 93); even mild malnutrition can substantially increase risks (93). Malnutrition's effects on disease are not unique to children; malaria and influenza both have general-population mortality rates proportionate to the degree of malnutrition (28).

While nutrition can strongly shape the course of infectious diseases, infection can also be an important driver of the onset of malnutrition even in the well-nourished (20, 26), impairing absorption (28) and affecting the microbiome (13). The high prevalence of disease in developing countries may be a major cause of malnutrition, independent of food scarcity or agricultural systems (2). Thus, malnutrition and disease interact in an important feedback loop affecting food and nutrition security: Infection makes malnourishment more likely [both biologically (Fig. 1*F*) and by reducing productivity and income (via Fig. 1 *B* and *H*)]; malnourishment leads to compromised immune function, increasing susceptibility, severity, and potentially transmission of infection (Fig. 1*G*); and more severe and widespread infections further worsen nutrition. Documentation of this feedback loop is especially clear for major infectious diseases that loom large in developing countries, including malaria, HIV, and diarrheal disease.

Disease Specific Evidence. Malaria infection can undermine nutrition in the initially well-nourished, and it is a major driver of chronic anemia in areas where it is endemic (24). At the same time, nutrition strongly shapes malaria outcomes: Low levels of key micronutrients account for a substantial proportion of malaria morbidity and mortality (26, 94). Improved childhood nutrition is likely to substantially reduce the burden of malaria in the developing world (2, 95, 96).

Even more complex feedbacks are present in the HIV epidemic, a key driver of nutrition insecurity in developing countries (20, 26). Not only are individuals with HIV prone to malnutrition and micronutrient deficiency from the disease (20, 26), but HIV strongly affects nutrition security indirectly via losses in productive labor force and resulting decreases in food production and income (especially in the agricultural sector).[§] Meanwhile, HIV/AIDS itself is shaped by nutritional status. Nutrient deficiency and weight loss are associated with more rapid progression and increased mortality (26); weight loss of only 5% can be predictive of death. In addition, malnutrition may increase transmission by those who are HIV-positive (26), worsening the epidemic.

Malnutrition is also a key risk factor for acquiring diarrheal disease, which has become the leading cause of childhood death in developing countries, and leads to mortality rates 14- to 24-fold higher from the disease (26, 97). Contaminated food and lack of access to clean water and sanitation are also major drivers, making agricultural production a potential contributor (23, 97) (*Environmental System* and Fig. 1 *C* and *E*). Because diarrheal disease reduces absorption of key nutrients, it is also a major cause of malnutrition in the developing world (with a particularly long-term impact on growing children), completing the feedback loop (97, 98).

Integrated Modeling of Infectious Disease and Nutrition Security. The field of infectious disease epidemiology has a strong tradition of mathematical and computational modeling (56–63), with applications to many of the diseases discussed above (99–101). Such models provide important insights into the core dynamics of these diseases, and could provide an important component of a systems approach to food and nutrition security.

However, epidemiological studies of infectious disease have rarely included detailed treatment of nutritional status (26). The relationship between nutrition and infection has been the focus of an increasing amount of recent research, as new evidence has emerged on the complexity of underlying mechanisms and mediating factors, such as microbiota (13, 25, 27). More research and better models of these complex dynamics are needed, along with their integration into population-level models of epidemiology (26–28). Most modeling of infectious disease progression and transmission is focused on individuals, and often does not capture longer time-horizon changes in environment, nutrition, or access to food (30). Given the growing empirical evidence regarding the strong relationship between nutrition and infectious disease, epidemiology models could gain much by taking food and nutrition dynamics into account. Similarly, both scientific study and policy efforts aimed at reducing malnutrition could gain much by incorporating rigorous models of infectious disease. Progress in management of infectious diseases would directly or indirectly make a major contribution to reduction in malnutrition (2), and the links between nutrition and disease are complex enough to make modeling an important source of new insights. Modeling techniques such as ABM and SD are already widely used in epidemiology (56–63, 102–104), where they offer advantages in capturing spatial and nonlinear dynamics, heterogeneity (56, 105), and adaptive behavior. We have argued (above) that these same advantages make their application to agri-food systems compelling. In addition to these advantages, the existing use of SD and ABM in epidemiology would facilitate direct integration of infection and disease models with agri-food models that address food and nutrition security from the perspective of food choice and availability. This would allow models to capture and explore many of the feedback loops identified above more rigorously.

Environmental System

Environmental systems affect the sustainability and future potential of agricultural food production, availability of water for both agriculture and human consumption, and patterns of weather and temperature. The relationship between the environment and agricultural food production is bidirectional and complex. Three dynamic pathways are likely to have an especially important impact on food and nutrition security.

Dynamic Pathways. The first dynamic pathway is feedback between demand-driven agricultural intensification and long-term sustainability of food yields. Global demand for food is expected to increase substantially in the coming decades, driven by population growth, urbanization, income growth, and growing demand for meat (20, 36, 44).[¶] Meeting demand will put new strain on agroecosystems, which provide 99% of the calories consumed by humans and cover almost a quarter of the earth's terrestrial surface (36, 40). Opportunities for further expansion of agriculture are limited, with growing competition from other land uses (36, 40). Increases in production are thus most likely to come from intensification of existing agriculture, carrying with it the risk of soil degradation through such processes as erosion, salinization, compaction, acidification, or nutrient depletion (Fig. 1*C*). Some evidence suggests such degradation may already be occurring (36, 44), and resulting yield reductions in agriculture on existing land may reach 50% by 2020 (106), further increasing pressure on agricultural production to meet demand. Both expansion and intensification of agriculture also reduce biodiversity, an important source of stability for ecosystems (36, 44), and may affect carbon, nitrogen, and hydrological cycles (35, 44, 45, 107). Neither losses in biodiversity nor negative ecosystem externalities are reflected in the individual-level, short-run incentives of food prices or production profits. However, these long-term costs are important factors for long-term food security. The combination of increasing demand for food, increasing soil degradation, and limited room for expansion of cultivated land will require careful management to avoid a destructive feedback loop: agricultural intensification depleting ecosystems, leading to reduced yields from agriculture, leading to still further intensification as agriculture tries to keep up with growing food demands (Fig. 1 *C* and *D*). Efforts to understand and manage food and nutrition security must take ecosystem dynamics of this kind into account. Food security means not only providing access to adequate food but avoiding "undue risk of losing such access" in the future (46).

A second pathway is competition for water. Agriculture represents the largest use of freshwater by humans (108), affecting both the quantity and quality of water available to other ecosystems and other sectors of human activity (36).Water plays a critical role in food production, with the 16–18% of cropland that is irrigated accounting for as much as 40% of global food production (36, 40). Demand for irrigation water has been increasing

---

[§] The age group most heavily affected by HIV is economically productive 25- to 50-y-olds, leading to a demographic gap in this age group in countries with high prevalence; agricultural sector production and incomes are often especially heavily affected (20).

[¶] The production of 1 kg of meat can require between 3 and 10 kg of grain (43), translating dietary change into much higher demands on agricultural production.

(108), and further intensification or expansion of agriculture implies further growth in demand. However, agriculture also faces increasing competition for water from other sectors, especially in developing countries with rapidly growing urban populations and industry (36). Increased diversion of water for agricultural intensification will worsen serious shortages of water in many regions. By the 1990s, at least 80 countries, with 40% of the world's population, were experiencing serious water scarcity (109). Even without accounting for climate effects, water scarcity is expected to affect 5 billion people by 2025 (110). Water shortages already have an important effect on health and disease (and thus on nutrition security) (33). Close to 1 billion people rely on unimproved water sources for drinking, cooking, and bathing (108), and lack of access to clean water is a major risk factor for diarrheal disease, contributing substantially to malnutrition (Fig. 1*E*). Urbanization in the developing world is likely to decrease access to clean water further (22). Conflict over water across political, ethnic, and socioeconomic boundaries has the potential to undermine food security if it erupts into violence (3) or produces large-scale migration (38, 39).

Climate effects represent a third pathway through which ecosystems may affect food and nutrition security (35). Although substantial uncertainty ranges surround estimates of climate change, recent evidence suggests changes are likely to have a major impact on agriculture and an important influence (mostly destabilizing) on food security (especially in smallholder systems) (29–34). Changes in temperature and precipitation may alter patterns of land suitability for agriculture (34), and water pressures are likely to increase, especially for the 82% of the world's agroecosystems completely reliant on rain (110). Weather conditions are likely to become more variable across time and space, producing greater fluctuations in crop yields and less stability in access to food, and potentially increasing the range and season of agricultural pests (34). Temperature and climate changes are also likely to affect disease burden, and thus indirectly undermine food security (30–34). Disease burden may, in turn, undermine management of ecosystems (33), and agricultural production can affect the course of climate change via the global carbon cycle (36) and greenhouse gas emissions (111). These potential feedbacks between agriculture/health and climate, along with spatially and temporally heterogeneous effects of climate change on food security and human behavior, represent an important focus for integrated modeling.

Integrated Modeling of Ecosystems, Climate, and Agriculture. As argued above, land-use and environmental dynamics can be key drivers of sustainable food production and nutrition security (42, 69, 110–113). A growing scientific literature uses mathematical and computational models to gain insight into processes of land-use change, ecosystem sustainability, and climate (66–73, 111–113). Integration of these modeling approaches and insights would add an important dimension to a dynamic and multilevel systems approach to agriculture (*Agri-food System*). Such integration would also benefit existing land-use and ecosystem models, which generally do not capture fully the complexity of human decision making about resource and land use or adaptive responses to environmental change. Linkage to sophisticated social science and agriculture models to capture coevolution of human and biological systems is likely to produce new and richer insights at the environmental level (42, 66, 112–114), and would benefit policy-makers (114). Computational simulations are widely used in environmental modeling, and ABM has recently been applied to natural resource and land-use management (66–73) and to individual land and economic decision making by agriculturalist households in the developing world (69, 113). Such models could form the basis for a promising integration with social science and economic models of food choice, social influence, and food availability (above), as well as integration with models of health and disease spread whose dynamics might be shaped by environmental factors. Leveraging the ability of complex systems modeling techniques to capture the interplay of multiple mechanisms, spatial dynamics, and individual interaction and adaptation, these combinations across scientific disciplines could provide a more theoretically and empirically grounded systems view of food and nutrition security outcomes.

Conclusion

Food and nutrition security remains a pressing global problem, with most countries experiencing one or both of the twin challenges of malnutrition and obesity. We have argued that the drivers of food and nutrition security are complex, multilevel, multisectoral, and heterogeneous. This paper reviewed structural components, feedback loops, and linkages between agri-food, health and disease, and environmental systems, which are key underlying drivers of sustainable food and nutrition security for smallholders and worldwide. These complex interconnections pose challenges for design of effective policy and for scientific study using many standard tools. Solving food and nutrition insecurity is likely to require the interdisciplinary collaboration of many actors across society, including health professionals, agriculturalists, food industrials, policy-makers, and scientists, as well as the use of unconventional approaches and tools. We have proposed that SD, ABM, and other computational systems science approaches could complement the present battery of epidemiological, environmental, and macroeconomic models to better capture the dynamic and adaptive processes involved at the juncture of these interconnected systems. This is essential to accelerate understanding of policy impacts in real time so that policy-makers, market entrepreneurs, and smallholder producers can access that information and contribute to finding appropriate responses.

However, many challenges must be addressed for such a multilayered systems approach to be realized. Interdisciplinary research is highly challenging, facing obstacles at every step in the research pipeline from education and training; through the organization of research and career advancement in universities; to the process of peer review, funding, and publication. Recently, recognition both of these challenges and of the pressing need for more interdisciplinary insights has driven research and policy shifts to help overcome these barriers. A recent National Academy of Sciences focus book identified promising trends and strategies in academia, industry, and government for facilitating interdisciplinary research (115), and identified roles all three sectors can play in furthering this goal. Policy-makers can help shape the research environment to facilitate the success of such efforts. In this paper, we have also identified existing building blocks in several different fields that would allow a strategy of incremental progress from existing work toward a systems vision. To accelerate progress, there is a need to develop integrative longitudinal databases on key processes and outcomes of agri-food, health, and environmental systems that are expected to have single and combined effects on food and nutrition security. Mapping of within- and cross-boundary knowledge is also a critical step toward realizing a systems approach and transdisciplinary tools for food and nutrition security, starting with a concrete understanding of existing knowledge about connections within and between systems.

To facilitate this task, we have described a systems framework that can serve as the basis for efforts to broaden the scope of policy and science in this area. We have examined three critical sectors (agri-food, health, and environment) in detail to identify key dynamic processes and existing modeling efforts that could serve as a focus for new data collection and as building blocks for systems modeling. Despite the challenges of implementation, we believe this type of systems approach is essential to generate important new insights and policy tools to combat food and nutrition insecurity today, and to help anticipate growing challenges that may threaten food and nutrition security in the near future.

ACKNOWLEDGMENTS. We thank Joe Ornstein, Julia Chelen, and Matthew Cherian for research assistance. Partial support was provided by a team grant on health as a driver of agri-food innovation (to L.D.) by The Quebec Fund for Social Sciences Research (Grant 137173).

1. FAO (1996) *Rome Declaration on World Food Security* (Food and Agriculture Organization, Rome).
2. Müller O, Krawinkel M (2005) Malnutrition and health in developing countries. *CMAJ* 173:279–286.
3. UNEP (2008) *Organic Agriculture and Food Security in Africa* (United Nations, New York).
4. von Braun J (2005) *The World Food Situation: An Overview* (International Food Policy Research Institute, Washington, DC).
5. Ogden CL, et al. (2006) Prevalence of overweight and obesity in the United States, 1999-2004. *JAMA* 295: 1549–1555.
6. Rennie KL, Jebb SA (2005) Prevalence of obesity in Great Britain. *Obes Rev* 6(1):11–12.
7. Kain J, Uauy R, Vio F, Albala C (2002) Trends in overweight and obesity prevalence in Chilean children: Comparison of three definitions. *Eur J Clin Nutr* 56: 200–204.
8. Mohammadpour-Ahranjani B, Rashidi A, Karandish M, Eshraghian MR, Kalantari N (2004) Prevalence of overweight and obesity in adolescent Tehrani students, 2000-2001: An epidemic health problem. *Public Health Nutr* 7:645–648.
9. Finucane MM, et al.; Global Burden of Metabolic Risk Factors of Chronic Diseases Collaborating Group (Body Mass Index) (2011) National, regional, and global trends in body-mass index since 1980: Systematic analysis of health examination surveys and epidemiological studies with 960 country-years and 9.1 million participants. *Lancet* 377:557–567.
10. National Institutes of Health (1998) Clinical guidelines on the identification, evaluation, and treatment of overweight and obesity in adults—The evidence report. *Obes Res* 6(Suppl 2):51S–209S.
11. Biro FM, Wien M (2010) Childhood obesity and adult morbidities. *Am J Clin Nutr* 91(Suppl):1499S–1505S.
12. Finkelstein EA, Ruhm CJ, Kosa KM (2005) Economic causes and consequences of obesity. *Annu Rev Public Health* 26:239–257.
13. Kelly P (2010) Nutrition, intestinal defence and the microbiome. *Proc Nutr Soc* 69:261–268.
14. Tanumihardjo SA, et al. (2007) Poverty, obesity, and malnutrition: An international perspective recognizing the paradox. *J Am Diet Assoc* 107:1966–1972.
15. Ericksen PJ (2008) Conceptualizing food systems for global environmental change research. *Glob Environ Change* 18:234–245.
16. Bates RH (1984) *Markets and States in Tropical Africa* (Univ of California Press, Berkeley).
17. Berger T (2001) Agent based spatial models applied to agriculture: A simulation tool for technology diffusion, resource use changes and policy analysis. *Agric Econ* 25:245–260.
18. Neff RA, Palmer AM, McKenzie SE, Lawrence RS (2009) Food systems and public health disparities. *J Hunger Environ Nutr* 4:282–314.
19. Hyden G (2007) Governance and poverty reduction in Africa. *Proc Natl Acad Sci USA* 104:16751–16756.
20. Bertozzi S, et al. (2006) Disease Control Priorities in Developing Countries, eds Jamison DT, et al. (World Bank, Washington, DC).
21. World Bank (2006) *Repositioning Nutrition as Central to Development: A Strategy for Large-Scale Action* (World Bank, Washington, DC).
22. Fotso JC, Ezeh AC, Madise NJ, Ciera J (2007) Progress towards the child mortality millennium development goal in urban sub-Saharan Africa: The dynamics of population growth, immunization, and access to clean water. *BMC Public Health* 7:218.
23. Wood S, et al. (2005) *Ecosystems and Human Well-Being: Current State and Trends*, eds Hassan R, Scholes R, Ash N (Island Press, Washington, DC).
24. Carneiro IA, et al. (2006) Modeling the relationship between the population prevalence of Plasmodium falciparum malaria and anemia. *Am J Trop Med Hyg* 75(2, Suppl):82–89.
25. Keusch GT (2003) The history of nutrition: Malnutrition, infection and immunity. *J Nutr* 133(Suppl): 336S–340S.
26. Tang AM, Smit E, Semba RD (2001) *Infections Disease Epidemiology: Theory and Practice*, eds Nelson KE, Williams CM (Aspen Press, Aspen, CO), pp. 383–406.
27. Schaible UE, Kaufmann SHE (2007) Malnutrition and infection: Complex mechanisms and global impacts. *PLoS Med* 4:e115.
28. Katona P, Katona-Apte J (2008) The interaction between nutrition and infection. *Clin Infect Dis* 46: 1582–1588.
29. Liu J, et al. (2010) A high-resolution assessment on global nitrogen flows in cropland. *Proc Natl Acad Sci USA* 107:8035–8040.
30. McMichael AJ (2002) Population, environment, disease, and survival: Past patterns, uncertain futures. *Lancet* 359:1145–1148.
31. McMichael AJ, Friel S, Nyong A, Corvalan C (2008) Global environmental change and health: Impacts, inequalities, and the health sector. *BMJ* 336:191–194.
32. Müller C, Cramer W, Hare WL, Lotze-Campen H (2011) Climate change risks for African agriculture. *Proc Natl Acad Sci USA* 108:4313–4315.
33. Myers SS, Bernstein A (2011) The coming health crisis: Indirect health effects of global climate change. *F1000 Biol Rep* 3:3.
34. Schmidhuber J, Tubiello FN (2007) Global food security under climate change. *Proc Natl Acad Sci USA* 104: 19703–19708.
35. Godfray HCJ, Pretty J, Thomas SM, Warham EJ, Beddington JR (2011) Global food supply. Linking policy on climate and food. *Science* 331:1013–1014.
36. Rosen C (2000) *World Resources 2000-2001: People and Ecosystems: The Fraying Web of Life* (World Resources Institute, Washington, DC).
37. Gentilini U, Webb P (2008) How are we doing on poverty and hunger reduction? A new measure of country performance. *Food Policy* 33:521–532.
38. Ruel MT (1998) Urban challenges to food and nutrition security International Food Policy and Research Institute, Food Consumption and Nutrition Division Discussion Paper No. 51 (International Food Policy and Research Institute, Washington, DC).
39. Crush J, Grant M, Frayne B (2007) Linking migration, HIV/AIDS and urban food security in Southern and Eastern Africa. *African Migration and Development Series No. 3* (Southern African Migration Project, Cape Town).
40. Cassman KG (2005) *Ecosystems and Human Well-Being: Current State and Trends*, eds Hassan R, Scholes R, Ash N (Island Press, Washington, DC).
41. Kates RW, Dasgupta P (2007) African poverty: A grand challenge for sustainability science. *Proc Natl Acad Sci USA* 104:16747–16750.
42. Lambin EF, Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. *Proc Natl Acad Sci USA* 108:3465–3472.
43. Matson PA, Parton WJ, Power AG, Swift MJ (1997) Agricultural intensification and ecosystem properties. *Science* 277:504–509.
44. Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. *Nature* 418:671–677.
45. Reganold JP, et al. (2011) Agriculture. Transforming U.S. agriculture. *Science* 332:670–671.
46. UNACCSN (1991) *Brief Policies to Alleviate Underconsumption and Malnutrition in Deprived Areas* (United Nations, NY).
47. Hammond RA (2009) Complex systems modeling for obesity research. *Prev Chronic Dis* 6:A97.
48. Sterman JD (2000) *Business Dynamics: Systems Thinking and Modeling for a Complex World* (Irwin McGraw–Hill, Boston).
49. Axelrod R (2006) *Handbook of Computational Economics: Agent-Based Computational Economics*, eds Tesfatsion L, Judd KL (Elsevier, Amsterdam), Vol. 2, pp. 1565–1584.
50. Janssen MA, Ostrom E (2006) *Handbook of Computational Economics: Agent-Based Computational Economics*, eds Tesfatsion L, Judd KL (Elsevier, Amsterdam), Vol. 2, pp. 1465–1509.
51. Tesfatsion L (2006) *Handbook of Computational Economics: Agent-Based Computational Economics*, eds Tesfatsion L, Judd KL (Elsevier, Amsterdam), Vol. 2, pp. 831–880.
52. Epstein JM (2007) *Generative Social Science* (Princeton Univ Press, Princeton).
53. Mabry PL, Marcus SE, Clark PI, Leischow SJ, Méndez D (2010) Systems science: A revolution in public health policy research. *Am J Public Health* 100:1161–1163.
54. Miller JH, Page SE (2007) *Complex Adaptive Systems: An Introduction to Computational Models of Social Life* (Princeton Univ Press, Princeton).
55. Axtell RL, et al. (2002) Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley. *Proc Natl Acad Sci USA* 99(Suppl 3):7275–7279.
56. Longini IM, Jr., et al. (2005) Containing pandemic influenza at the source. *Science* 309:1083–1087.
57. Eubank S, et al. (2004) Modelling disease outbreaks in realistic urban social networks. *Nature* 429:180–184.
58. Ferguson NM, et al. (2006) Strategies for mitigating an influenza pandemic. *Nature* 442:448–452.
59. Germann TC, Kadau K, Longini IM, Jr., Macken CA (2006) Mitigation strategies for pandemic influenza in the United States. *Proc Natl Acad Sci USA* 103: 5935–5940.
60. Halloran ME, et al. (2008) Modeling targeted layered containment of an influenza pandemic in the United States. *Proc Natl Acad Sci USA* 105:4639–4644.
61. Epstein JM (2009) Modelling to contain pandemics. *Nature* 460:687.
62. Yang Y, et al. (2009) The transmissibility and control of pandemic influenza A (H1N1) virus. *Science* 326: 729–733.
63. Lee BY, et al. (2010) A computer simulation of vaccine prioritization, allocation, and rationing during the 2009 H1N1 influenza pandemic. *Vaccine* 28:4875–4879.
64. Heckbert S, Baynes T, Reeson A (2010) Agent-based modeling in ecological economics. *Ann N Y Acad Sci* 1185:39–53.
65. Parker DC, et al. (2003) Multi-agent systems for the simulation of land-use and land-cover change: A review. *Ann Assoc Am Geogr* 93:314–337.
66. Evans TP, et al. (2006) Spatially explicit experiments for the exploration of land-use decision-making dynamics. *Int J Geogr Inf Sci* 20:1013–1037.
67. Bithell M, Brasington J (2009) Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution. *Environ Model Softw* 24(2):173–190.
68. Schluter M, Pahl-Wostl C (2007) Mechanisms of resilience in common-pool resource management systems: An agent-based model of water use in a river basin. *Ecology and Society*, 12(2):4 [online] URL: http://www.ecologyandsociety.org/vol12/iss2/art4/.
69. Bone C, Alessa L, Altaweel M, Kliskey A, Lammers R (2011) Assessing the impacts of local knowledge and technology on climate change vulnerability in remote communities. *Int J Environ Res Public Health* 8:733–761.
70. Hailegiorgis AB, et al. (2010) An agent based model of climate change and conflict among pastoralists in east Africa. *Proceedings of the 2010 International Congress on Environmental Modelling and Software* (Fairfax, VA). Available at http://cs.gmu.edu/~eclab/projects/mason/publications/climate10.pdf.
71. Evans TP, Kelley H (2004) Multi-scale analysis of a household level agent-based model of landcover change. *J Environ Manage* 72(1-2):57–72.

72. Dube L, Beauvais J, Fresco L, Webb P (2010) *Obesity Prevention: The Role of Brain and Society on Individual Behavior* (Elsevier, San Diego).
73. Lock K, et al. (2010) Health, agricultural, and economic effects of adoption of healthy diet recommendations. *Lancet* 376:1–11.
74. Dekle R, Vandenbroucke G (2012) A Quantitative Analysis of China's Structural Transformation. *Journal of Economic Dynamics and Control* 36:119–135.
75. Young A (2003) Gold into base metals: Productivity growth in the People's Republic of China during the reform period. *J Polit Econ* 111:1220–1261.
76. Zhang L, Huang J, Rozelle S (2002) Employment, emerging labor markets, and the role of education in rural China. *China Econ Rev* 13:313–328.
77. Timmer CP (1995) Getting agriculture moving: Do markets provide the right signals? *Food Policy* 20: 455–472.
78. Timmer CP (2012) Behavioral dimensions of food security. *Proc Natl Acad Sci USA* 109:12315–12320.
79. Webb P, Block S (2004) Nutrition information and formal schooling as inputs to child nutrition. *Econ Dev Cult Change* 52(4):801–820.
80. Altieri MA (2004) Linking ecologists and traditional farmers in the search for sustainable agriculture. *Front Ecol Environ* 2:35–42.
81. Kruijssen F, Keizer M, Giuliani A (2009) Collective action for small-scale producers of agricultural biodiversity products. *Food Policy* 34:46–52.
82. Rietbergen S, Bishop J, Mainka S (2002) *Ecosystem Conservation—A Neglected Tool for Poverty Reduction* (International Institute for Environment and Development, Regional and International Networking Group, London, UK).
83. Hawkes C (2009) Identifying innovative interventions to promote healthy eating using consumption-oriented good supply chain analysis. *J Hunger Environ Nutr* 4:336–356.
84. Devaux A, et al. (2009) Collective action for market chain innovation in the Andes. *Food Policy* 34:31–38.
85. Reardon T, Timmer CP, Barrett CB, Berdegue J (2003) The rise of supermarkets in Africa, Asia, and Latin America. *Am J Agric Econ* 85:1140–1146.
86. Reardon T, Henson S, Gulati A (2010) *Trade, Food, Diet and Health: Perspectives and Policy Options*, eds Hawkes C, et al. (Wiley, Hoboken, NJ).
87. Reardon T, Timmer CP, Minten B (2012) Supermarket revolution in Asia and emerging development strategies to include small farmers. *Proc Natl Acad Sci USA* 109:12332–12337.
88. Pingali P (2010) *Obesity Prevention: The Role of Brain and Society on Individual Behavior*, eds Dube L, et al. (Elsevier, San Diego).
89. Webb P, Block S (2012) Support for agriculture during economic transformation: Impacts on poverty and undernutrition. *Proc Natl Acad Sci USA* 109:12309–12314.
90. Pelletier DL, Frongillo EA, Jr., Schroeder DG, Habicht JP (1994) A methodology for estimating the contribution of malnutrition to child mortality in developing countries. *J Nutr* 124(Suppl):2106S–2122S.
91. Scrimshaw NS (2003) Historical concepts of interactions, synergism and antagonism between nutrition and infection. *J Nutr* 133(Suppl):316S–321S.
92. Wolowczuk I, et al. (2008) Feeding our immune system: Impact on metabolism. *Clin Dev Immunol* 2008: 639803.
93. Caulfield LE, de Onis M, Blössner M, Black RE (2004) Undernutrition as an underlying cause of child deaths associated with diarrhea, pneumonia, malaria, and measles. *Am J Clin Nutr* 80(1):193–198.
94. Shankar AH (2008) *Nutrition and Health in Developing Countries*, eds Semba RD, Bloem MW (Humana Press, Totowa, NJ), pp. 229–274.
95. Ehrhardt S, et al. (2006) Malaria, anemia, and malnutrition in African children—Defining intervention priorities. *J Infect Dis* 194:108–114.
96. Zeba AN, et al. (2008) Major reduction of malaria morbidity with combined vitamin A and zinc supplementation in young children in Burkina Faso: A randomized double blind trial. *Nutr J* 7:7.
97. Lanata CF, Black RE (2008) *Nutrition and Health in Developing Countries*, eds Semba RD, Bloem MW (Humana Press, Totowa, NJ), pp. 139–178.
98. Guerrant RL, Oriá RB, Moore SR, Oriá MO, Lima AA (2008) Malnutrition as an enteric infectious disease with long-term effects on child development. *Nutr Rev* 66:487–505.
99. May R, Anderson RM (1992) *Infectious Diseases of Humans: Dynamics and Control* (Oxford Univ Press, Oxford).
100. McKenzie FE (2000) Why model malaria? *Parasitol Today* 16(12):511–516.
101. Ngwa WS (2000) A mathematical model for endemic malaria with variable human and mosquito populations. *Math Comput Model* 32:747–763.
102. Flessa S (1999) Decision support for malaria-control programmes—A system dynamics model. *Health Care Manage Sci* 2:181–191.
103. Thompson KM, Duintjer Tebbens RJ (2008) Using system dynamics to develop policies that matter: Global management of poliomyelitis and beyond. *System Dynamics Review* 24:433–449.
104. Rahmandad H, Sterman JD (2008) Heterogeneity and network structure in the dynamics of diffusion: Comparing agent-based and differential equations models. *Manage Sci* 54:998–1014.
105. Kandala NB, Madungu TP, Emina JB, Nzita KP, Cappuccio FP (2011) Malnutrition among children under the age of five in the Democratic Republic of Congo (DRC): Does geographic location matter? *BMC Public Health* 11:261.
106. Mantel S, van Engelen VWP (1997) *The Impact of Land Degradation on Food Productivity: Case Studies of Uruguay, Argentina, and Kenya: Main Report*. Report 97/01 (International Soil Reference and Information Centre/United Nations Environment Programme, Wageningen, The Netherlands), Vol 1.
107. Conway G (2007) *The Doubly Green Revolution: Food For All in the Twenty-First Century* (Penguin, London).
108. United Nations (2009) *The Millenium Development Goals Report 2009* (United Nations, New York).
109. Hassan R, Scholes R, Ash N, eds (2005) Janetos. *Ecosystems and Human Well-Being: Current State and Trends* (Island Press, Washington, DC).
110. World Resources Institute (2005) *World Resources Report: The Wealth of the poor – Managing Ecosystems to Fight Poverty* (World Resources Institute, Washington, DC).
111. United Nations Environment Programme (2000) *IPCC Special Report: Emissions Scenarios* (Intergovernmental Panel on Climate Change, Geneva).
112. Pahl-Wostl C, Sendzimir J, Jeffrey P (2009) Resources management in transition. *Ecology and Society* 14 (1):46. Available at http://www.ecologyandsociety.org/vol14/iss1/art46/.
113. Manson SM, Evans T (2007) Agent-based modeling of deforestation in southern Yucatan, Mexico, and reforestation in the Midwest United States. *Proc Natl Acad Sci USA* 104:20678–20683.
114. Zellner ML (2008) Embracing complexity and uncertainty: The potential of agent-based modeling for environmental planning and policy. *Plann Theory Pract* 9:437–457.
115. Committee on Science, Engineering, and Public Policy (2004) *Facilitating Interdisciplinary Research* (National Academies Press, Washington, DC).