Setting priorities to address the research gaps between agricultural systems analysis and food security outcomes in low- and middle-income countries

Working Paper No. 255

CGIAR Research Program on Climate Change,
Agriculture and Food Security (CCAFS)

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Abstract

This document assesses the current state of practice for the representation of food security indicators in agricultural systems models and provides recommendations for improvements in both model formulation and the empirical evidence base underlying it. This assessment was based on a review of existing conceptual frameworks linking agriculture and food security, the indicators most commonly used to represent food security dimensions (availability, access, utilization and stability) and studies using models to assess household and regional food security. We also undertook proof-of-concept analyses using household-level and regional-level models incorporating food access indicators into two agricultural systems models.

We found that there is a broad agreement at a conceptual level about important linkages between agricultural systems and food security, at least for some populations. Despite this consensus, the extant conceptual frameworks often are not specific enough about both food security indicators and linking pathways to provide guidance for the integration of food security into agricultural systems models. Our review of the Food Environments literature indicates that it currently emphasizes a broad range of environmental and personal factors that influence food choice in higher-income country settings, but additional work is necessary to apply these concepts to low- and middle-income countries, and to populations of agricultural producers.

The representations of food security indicators in empirical model analyses of both households and regions are diverse yet often inconsistent with the definitions more commonly emphasized by human nutritionists. Often, empirical models appear to equate measures of production or yields with “food security” when these are indicators only of the “availability” dimension of food security. In general, agricultural system model analyses more commonly employ *availability* indicators (which can be viewed as a necessary but not sufficient condition for “food security”) but would provide improved guidance for research and programmatic efforts with a focus on indicators of *food access*. Even when dynamic models are specified, the time units, time horizons and criteria to evaluate the “stability” dimension of food security often are not adequate.

We recommend that agricultural systems models focus on incorporating three food access indicators: 1) food consumption expenditures, 2) experience-based food insecurity scales such as the Food Insecurity Experience Scales (FIES) or the Household Food Insecurity Access Scale (HFIAS) instruments, and 3) measures of household dietary diversity such as the Household Dietary Diversity Score (HDDS). These indicators are preferable because of the limited empirical relationship between national-level availability and individual nutritional status and because capturing own production on farms or production at regional scales is not sufficient for understanding households' and individuals' experience of food insecurity, which entails considerable access to markets, dependence on food prices, and interactions with diverse food environments. Moreover, these indicators should also be evaluated over time using the approaches like that developed by Herrera (2017) to assess more formally the robustness and adaptability components defining food security stability.

The evidence base is currently insufficient to support robust and reliable integration of experience-based food insecurity scales and household dietary diversity into agricultural systems models. Although a number of studies have examined the determinants of these indicators and found a few consistent relationships (e.g., higher household incomes improve all indicators) often these are not specific to the settings modeled by existing agricultural systems models. This suggests that collection of this information, preferably using longitudinal data approaches, is needed so that model extensions can include these indicators.

Additional study (implying larger and longer-term investments) is needed to document and refine the general nature of relationships between common outputs of agricultural systems models and the other two indicators of food access (food insecurity and household dietary diversity scales). There is also undoubtedly much work to be done to determine appropriate analytical (statistical) techniques, theoretical foundations and functional forms linking determinants to these and other indicators for the purposes of agricultural systems modeling but even more simplistic, reduced form empirical relationships may be useful as this body of work is explored and expanded.

Priorities for application of agricultural systems models integrating improved representations of food security indicators could include assessment of shocks that could negatively affect production or incomes (e.g., weather, pests, disease, rapid changes in market conditions or access). Other key assessments could include longer-term processes that could negatively affect food security such as climate change (both effects of changes in rainfall and temperature distribution and evaluation of adaptation strategies), land use change, land fragmentation (or consolidation policies), decreases in biodiversity, natural resource degradation and demographic shifts (migration to urban areas).

Our proof-of-concept analyses incorporating food access indicators at the household and regional levels have highlighted the empirical challenges of doing so, but also the benefits of doing so. For example, the household-level analysis using the CLASSES model indicated that for two different households, food security outcomes are not “robust” with respect to a yield shock but demonstrate “adaptability” in returning to close to pre-shock conditions. The CLASSES model also indicates the desirability of incorporating multiple alternative measures of food security, because these respond differently over time in the face of a shock.

We recommend broad dissemination of the findings of this study to the agricultural systems modeling community and to the nutrition community (those working in the agriculture-nutrition space in particular). We encourage investments to support development of a broader base of empirical evidence about the determinants of food access indicators and their linkages to variables included in agricultural systems models, and efforts to extend existing agricultural systems models to include improved representations of food access indicators and intra-household food security outcomes. Moreover, further assessment is merited of the costs and benefits of representing utilization indicators (such as nutritional status) in agricultural systems models.

Keywords

Farming systems; Food access; Food security; Mathematical models.

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Contents

1. Introduction

The linkages between agriculture and nutrition-related outcomes—including food security outcomes—have long been recognized in various conceptual frameworks. Actions based on these linkages have become more prominent during the past decade with efforts such as the United Nations Scaling Up Nutrition and other organizational efforts to "mainstream nutrition" into sectors beyond health (IFAD, 2014). In particular, nutritional considerations have become more important in the design and implementation of agricultural development projects and best practices have been proposed (e.g., FAO, 2013; Garrett, 2017). Although agriculture is only one among many factors influencing food security outcomes, for certain populations and regions the linkages between food security outcomes and the performance of agricultural systems are vitally important—particularly in light of ongoing environmental challenges due to soil degradation, water availability and global climate change.

Despite the recognition of these important linkages and challenges, there are a limited number of studies that include explicit quantitative analysis of the linkages between food security outcomes and agricultural systems. In a review of previous research for a special issue of Agricultural Systems of papers compiled from the 2nd International Conference on Global Food Security in 2015, Stephens et al. (2018) noted the gap between conceptualization and quantitative implementation of linkages between agricultural systems outcomes and food security, stating:

An emphasis on measuring household or individual level access to food, and understanding the dietary or nutritional impacts of changes to agricultural systems are conspicuously underrepresented…

They ultimately concluded that:

…further work is needed to examine the interfaces between agricultural systems, food systems and food security, including examination of agricultural produce markets, value chains, international exports and imports of agricultural commodities, food demand and preferences and constraints (so called 'food environments' Herforth and Ahmed, 2015).

A few studies (e.g., Stephens et al. 2012, Kopainsky and Nicholson, 2015) have tried to link agricultural systems models with food security outcomes to understand evolving intertemporal dynamics and assess the impacts of system intensification. However, such studies appear to be small in number and are limited by the use of rudimentary indicators of food security (e.g., proportion of household caloric needs) and a focus only on household-level outcomes.

Thus, there is a crucial need for—and a large potential benefit to—additional exploration of the "uncharted territory" (Stephens et al., 2018) linking agricultural systems analysis and food security outcomes in a broader sense. This paper provides a further update on the current state of literature encompassing quantitative linkages between agricultural systems analysis and food system outcomes, identifies priority research actions for improving the quantitative analysis of such linkages at household and regional scales, and illustrates how the integration of food security indicators into agricultural systems models might be done with a proof-of-concept case analysis.

Objectives

This working paper has the following objectives:

1. Additional review and assessment of systems-oriented conceptual frameworks that link food security outcomes to other components of agricultural systems, building on the discussion in Stephens et al (2018);
2. Additional review and assessment of previously-developed quantitative models that link agricultural system outcomes and food security outcomes, also building on the discussion in Stephens et al (2018);
3. Delineation of priority research themes and contexts that would facilitate analysis of key linkages between quantitative agricultural systems analysis (with an emphasis on systems modeling) and a relevant set of food security outcomes at household and regional scales;
4. Describe a proof-of-concept case analysis illustrating the process of integration and the usefulness of explicit consideration of linkages.

2. Scope of the assessment

A few clarifications and caveats are appropriate to more clearly delineate the scope of this assessment. A principal purpose of this document is to provide guidelines and recommendations for improvement of the practice of modeling food security outcomes using agricultural systems models. Although not categorically excluding other types of analyses from our discussions, we generally imply by the term 'agricultural systems model' an empirical model that includes biophysical content, sometimes complemented by economic content because both of these elements can be necessary (if not sufficient) for an assessment of linkages between agriculture and food security indicators. Often, this will comprise a simulation model (of one or more types) that is used for the assessment of counterfactual situations compared to a baseline or *status quo* situation—in contrast to a purely statistical model that is used primarily to determine the nature of associations between variables[1]. Although our assessment of the literature has turned up many types of models, our focus in this assessment is on how to better represent food security outcomes in those models fitting our definition of an 'agricultural systems model'. The extensive literature on agriculture, food security, and systems models required us to impose some limits on our review.

Many agricultural systems models focus at the plot, farm, household or landscape level due to their focus on biophysical dimensions of agricultural production. In contrast, many models assessing food security outcomes tend to be focused on the household or on national or regional markets. In general, our focus is on food security outcomes for households that have an active role in agriculture, rather than for all households in a given region. This is consistent with common practice for household-level agricultural systems models, as illustrated by analyses such as Stephens et al. (2012) and Wossen et al. (2018). However, there are examples of analyses that integrate households across regional markets (e.g., the agent-based modeling work of Bakker et al., 2018) that could

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[1] We acknowledge that some studies (i.e., Harttgen et al., 2016) develop simulations based on a previously-estimated statistical model, but most simulation models use a variety of relationships that are not purely statistical.

readily be extended to assess the impacts on non-agricultural households (e.g., urban residents not producing their own food). Despite our focus on agricultural households so that biophysical, economic and food security outcomes can be more closely linked, the basic approach we employ could in principle be applied to other simulation model settings at various scales, including analysis of non-farming households for whom representing consumption decisions would be most relevant. We define “regional” as a higher level of aggregation than an individual household, which can encompass various spatial aggregations (typically, at the level of a country or its subregions).

Our focus on agricultural systems models and food security has a number of implications. First, although there is broad and continuously-growing literature on the linkages between agriculture and food security or food and nutrition security (reflected, e.g., in the development of ‘nutrition-sensitive agriculture’ and related analyses), we generally limit our review to those analyses that have been formalized in development of empirical (and simulation) models. The broader literature linking agriculture to food security outcomes can be a valuable complement to the development of improved agricultural systems models, but we deemed a comprehensive review of this literature as outside of the scope of this document.

We have provided only cursory treatment of linkages between agricultural systems and intra-household (individual) food security outcomes, despite its acknowledged importance, particularly for women and children. We have done so in part because of the quite limited treatment of intra-household outcomes in the existing agricultural systems modeling literature, and because we believe additional assessment of the costs and benefits of alternative approaches to modeling intra-household disaggregation is merited. We offer some assessments of the current state of practice of intra-household representations throughout.

Finally, although food security frequently is defined to include four elements (availability, access, utilization and stability) we focus much of our discussion on the access and stability dimensions. As we note below, the availability component is often the most easily measured and represented in agricultural systems models, but improved availability should generally be thought of as necessary but not sufficient for improved food security, given the somewhat hierarchical nature of these four elements[2]. Thus, we believe it is both necessary and useful for agricultural systems models to transcend the use of only availability measures. Utilization typically comprises food actually consumed by individuals and the resulting individual nutritional outcomes. Often, these outcomes are described as related to "food and nutrition security" (FNS), which certainly has considerable overlap with our treatment of "food security." However, because the utilization component often has substantive interactions with health status (see, e.g., Randolph et al., 2007) that are challenging to represent in agricultural systems models, we do not focus on the utilization component of food security. However, we note in the conclusions some recommendations for follow-on work that could encompass the broader concept of FNS.

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[2] For example, access will necessarily be restricted without adequate availability, but increased availability (say, through increased production) does not imply that access will be improved for a substantive number of people.

3. Review of existing conceptual frameworks linking agricultural systems and food security

Conceptual frameworks that link food security outcomes to other components of agricultural systems provide a starting point for examining research gaps between agricultural systems analysis and food security outcomes. There is a large and growing literature that hypothesizes and documents the linkages between agriculture, nutrition and health. Our objective here is to review the conceptual bases that have been offered for these linkages, with two main purposes related to our assessment of food security outcomes using agricultural systems models. First, a review of the conceptual basis indicates the degree of consensus regarding the underlying nature of these relationships, which can be used to motivate their explicit inclusion in agricultural systems models. Second, this review provides a means of reviewing hypothesized pathways and effects that may be useful to guide the development of agricultural systems models with explicit linkages to food security for specific contexts. Thus, we undertook a review of a variety of conceptual frameworks, including those that focus on food and nutrition security as well as those that represent a more general "food system". We began reviewing frameworks with which the authors were already familiar and additional relevant frameworks were identified in SCOPUS using the search terms "food security conceptual framework." We also offer comments on how the existing frameworks might be modified or complemented to facilitate their use in the development of quantitative (especially structural) modeling approaches.

The literature on conceptual frameworks that link agriculture with food security is growing, and early frameworks that differentiate between food system activities, outcomes and drivers (cf. Ingram et al., 2010) are being refined (e.g., by the explicit discussion of the role of diets as a core link between food systems and their nutrition and health outcomes (HLPE, 2017) and extended (e.g., by the explicit discussion of the political system and governance issues, e.g., Braun & Birner, 2017; Wegener et al., 2012). Existing conceptual frameworks that link food security outcomes to other components of agricultural systems share a number of features and components. Many frameworks acknowledge that food systems are complex and adaptive systems that are composed of:

- Food system activities such as food production, processing, distribution, and consumption.
- The resources going into these activities.
- Outcomes of these activities, spanning from food security to environmental and social welfare outcomes.
- Actors, institutions, and organisms whose decentralized behavior and interaction shape and modify food system activities and resource use and whose behavior and interaction might change in response to food system outcomes.
- Feedback and interdependence across levels and scales.

Nearly all of the frameworks recognize that a wide variety of factors—not just agriculture—affect food security outcomes for both households involved in agriculture and those that are not. More recent additions to existing frameworks are the concepts of food environments and resilience. Food environments describe the physical, economic, political and socio-cultural context in which consumers engage with the food system to acquire, prepare and consume food (HLPE, 2017). Resilience refers to the capacity of the food system to provide food security over time and despite disturbances (Tendall et al., 2015). There are three generic potential responses for food systems when they are affected by disturbance (Walker et al., 2004):

- *Stability or robustness:* the system does not exhibit changes in its behavior. Stability describes a behavior that follows the same trajectory as it would without a disturbance.
- *Adaptation:* the behavior of the system bends when affected by a disturbance but eventually, it bounces back to the behavior over time of a system without a disturbance.
- *Transformation:* the system as it currently exists breaks and changes into a new system with different structure, relationships and identity. The new system might or might not produce the same outcomes (e.g., food security). Whereas some transformations might be positive, risk management is often concerned with those transformations that are not and with cases in which the system might collapse.

In general, the above criteria as defined are most relevant for the consideration of (often, unintended) shocks that would have a negative impact on food security (such as drought, pests, disease or conflict). For the analysis of (often, intended) interventions to improve food security outcomes (such as productivity-enhancing technologies), "stability" (no change) or "adaptation" (return to previous conditions) would generally be considered less than desirable. (We illustrate this with our proof-of-concept analysis with the Mexico Sheep Sector Model, p. 65 below.) This suggests the need to more carefully define the meanings of these indicators with respect to the analyses to be undertaken, in addition to more clearly defining what constitutes "stability" and "adaptation." In addition, it is generally more challenging to assess the "transformation" component in agricultural systems models, and this appears less common in the literature we review below. Although dynamic models (perhaps most particularly agent-based model analyses) could in principle capture some types of transformative change, it may be adequate for analyses with a time frame extending to only a few years to focus on the first two of these responses to system shocks or evolution.

Herrera (2017) develops a series of metrices that can be calculated with dynamic simulation models to assess stability or robustness, adaptation and transformation in social-ecological systems. The metrices help a) anticipating whether robustness, adaptation or transformation can be expected as a result of a given disturbance, b) identifying where the thresholds are between robustness, adaptation and transformation and c) understanding what the resources and drivers are that foster robustness, adaptation and transformation. The metrices described in Herrera (2017) all refer to the impact of a disturbance (defined as the multiplication of the extent of a shock and the duration thereof) with respect to an outcome function. The outcome function describes the behavior over time of variables or indicators of interest such as food security indicators. The impact of a disturbance is usually measured by comparing the time-dependent behavior of the outcome function with the reference behavior of the same function, that is, with the time-dependent behavior of the outcome function in the absence of a disturbance. Four main resilience metrices discussed in Herrera (2017) are:

- *Hardness*: The ability of the system to withstand a disturbance without experiencing a change in the performance of the outcome function F(x) (the threshold value between robustness and adaptation).
- *Recovery rapidity*: The average rate at which the system returns to the reference behavior of the outcome function (i.e., returns to the same steady state, pathway or regime).
- *Elasticity*: The ability of the system to recover from a disturbance without changing to a different steady state or regime (the threshold value between adaptation and transformation).
- *Index of resilience*: The probability of keeping the current steady state or regime.

Hardness and elasticity indicators are examined more specifically for the two proof-of-concept models (in Section 7).

Appendix 1 provides a more detailed overview of the conceptual frameworks in diagrams and tabular form (Appendix Table A1). The myriad of frameworks seems to serve different purposes:

Some provide a high-level perspective on the interconnected nature of agricultural systems and food-related outcomes. These frameworks illustrate that food security both depends on and influences agricultural systems. Examples of this type of conceptual frameworks are: Fanzo et al., 2017; IOM, 2015; Neff & Lawrence, 2015; Sobal et al., 1998.

Another set of frameworks provides more details about the connections between environmental, farming, economic and social sectors. They identify and visualize the major subsystems and key connections among them. Examples of this type of conceptual framework are in Fanzo, et al., 2017; HLPE, 2017; Horton et al., 2016; Ingram, et al., 2010; Pinstrup-Andersen & Watson II, 2011; Wegener, et al., 2012.

A last category of frameworks has a somewhat narrower focus but describes the specific pathways linking agricultural systems and food and nutrition security. Examples of this type of conceptual frameworks are: Acharya et al., 2014; Hammond & Dubé, 2012; K. Suneetha et al., 2014; Kanter et al., 2015.

Maybe the most comprehensive effort at conceptualizing the linkages between agricultural systems and food and nutrition security is the global food system map that depicts the inter-related concepts and challenges that connect the global food system (Figure 1; ShiftN, 2009).

Discussion of existing frameworks to support modeling linkages between agricultural systems and food security

Many of the frameworks discussed above provide insights about how to model the linkages between agricultural systems and food security. The most useful for the purposes of systems model development tend to be those that focus on food security and specify pathways linking agriculture to food and nutrition outcomes. These include frameworks presented in Kadiyala et al (2014), Randolph et al. (2007), Dobbie and Balbi (2017), Garrett (2017), Kanter et al. (2015) and Sassi (2018). The illustrative pathways in these frameworks suggest more directly the mechanisms (variables and relationships) by which agricultural systems outcomes and food security outcomes are linked. Many of the frameworks are quite high-level and describe very general relationships rather than specific pathways. Perhaps the most notable example is from Wossen et al (2018), for which “Adaptation” is directly linked to “Food Security” in one-way causality. These higher-level depictions can be useful as conceptual guidelines, but they provide limited support for quantitative model development and assessment of interventions because they are not sufficiently specific about quantitative indicators and impact pathways. (In some cases, “policy” is viewed as a higher-level determinant of food security, but simply stating that is not sufficiently specific to provide insight about how to change policy.) The ShiftN (2009) food system diagrams have a greater level of complexity and begin to delineate pathways, but they don’t really focus clearly on food security.

Most of the frameworks (even some that focus on food security) do not include all elements of availability, access, utilization and stability. Especially the latter is more frequently ignored, as discussed further below. In addition, it is often not clear if these are viewed as some sort of hierarchy (especially the availability-access-utilization linkages) or whether they are separate. In some cases, access causes availability in a diagram, in other cases, it is the reverse. Related to this is the frequent absence of delineating levels of analysis (, data or outcomes. Most of the frameworks also do not include specific indicators for food security or nutrition outcomes. It is common to have the outcome be "food security" or "nutritional status" and only a few mention specific indicators at the household level such as dietary diversity (e.g., Kanter et al, 2015). This higher-level approach may be appropriate for the intended purposes of the frameworks, but they may not provide much guidance to quantitative model developers.

Many frameworks are also not particularly clear about which actors are covered and who makes what decisions. This is relevant models often need to specify one or more decision makers at multiple scales. The Hawkes (2009) and Hawkes et al. (2012) frameworks use an Actors-Processes-Outcomes framework, but this is quite high level and "processes" include "ag inputs" that are not always clearly defined. Arachya et al. (2014) includes producers, "food chain actors" and consumers. "Consumers" or "households" are frequently represented (e.g., Garrett, 2017; Ecker and Breisinger, 2012). Sometimes the frameworks delineate "levels" (e.g., national, regional, community, household, individual) with specific effects or outcomes of interest for each (e.g., the Food Insecurity and Vulnerability Information and Mapping System (FIVIMS), FAO, 2000).

Few of the frameworks address intra-household food security issues. Of the more than 50 frameworks reviewed (and summarized in Appendix 1), only 4 had explicit treatment of individuals with the household, focused on children (especially for nutritional status) and women. Three other frameworks implied treatment of individuals (e.g., Sassi 2018 mentions "individual food and nutrition pathways") but in general the conceptual treatment of the linkages determining intra-household food security status is limited. Although we acknowledge that we did not search for frameworks specifically addressing intra-household allocation and outcomes, the limited treatment of this issue in more general frameworks suggests the need for a reconsideration of the treatment of intra-household issues from both the conceptual and empirical perspective.

Most of the frameworks do not specifically represent intertemporal dynamics or feedback processes, both of which would be important to represent the "stability" component of food security. “Stability” is also at times referred to by the broader concept of “resilience”. Intertemporal change is admittedly a challenging concept to represent in a two-dimensional diagram, but improvements to existing frameworks would seem possible in this regard. Some frameworks discuss general resilience concepts (e.g., Tendall et al., 2015; FAO, 2016), but the linkages to the stability component of food security are not explicit. Burchi et al. (2011) depict stability in a framework that primarily defines the four components of food security but include suggested actions and strategies to promote stability of food availability, access and utilization. Allen and Prosperi (2016) integrate resilience concepts into the Ericksen (2008) and Ingram (2011) frameworks.

Many of the frameworks also depict a linear cause-and-effect model with limited feedbacks among system elements determining food security outcomes. Representation of feedback is relevant because—as noted above—these systems demonstrate feedback and interdependence within and across levels. Appropriate representation of feedback processes is relevant, particularly when considering proposed agriculture-based interventions designed to improve food security outcomes. The systems modeling literature (e.g., as summarized in Sterman, 2000) has long since noted that feedback processes, accumulation and non-linearities result in “dynamic complexity”, which gives rise to “policy resistance” (the intended effects of interventions will be delayed or largely offset) and “unintended consequences” (other, often negative, effects may occur in response to interventions; short-term and long-term impacts of system changes can differ). Thus, understanding and appropriately representing feedback processes in conceptual frameworks and quantitative models will often be both necessary and appropriate. Moreover, feedback representations provide a specific link with intertemporal dynamics that is often appropriate, as noted above. Most intertemporal quantitative models include at least some feedback processes that link system elements over time, so an understanding of which feedback processes are likely to be important conceptually is relevant for empirical model development (including data collection efforts).

The frameworks that do represent feedback processes tend to include only a few such linkages that differ for each diagram. General resilience frameworks (e.g., IOM 2015;

FAO, 2016, Tendall et al. 2015) tend to represent changes in high-level "state" (key variables) over time. The high-level framework from Hammond and Dube (2012) indicates feedback processes (and some specific mechanisms) among the "agri-food", "environmental" and "health/disease" components of the system that determines food and nutrition security. One of the more common inclusions is feedbacks between the food system (or agriculture) and environmental outcomes (Lawrence, 2015; Horton et al., 2016; Burchi et al., 2011; Ericksen, 2008; Ingram 2011; Allen and Prosperi, 2016; ShiftN, 2009). Frameworks that focus on household assets and livelihood strategies (e.g., Kadiyala et al., 2014; Ashley and Carney, 1999; World Food Programme, 2012) tend to link livelihood outcomes (including food security) back to increases in household assets in a reinforcing feedback loop. Similarly, the UNICEF (1998) framework shows a reinforcing feedback process where lack of initial livelihood assets limits improvements in child nutritional status—with ongoing intertemporal effects.

Other frameworks focus on feedbacks between consumer decisions and the structure of food supply chains and food environments (e.g., Pinstrup-Andersen and Watson, 2011; HLPE, 2017; Arachya et al, 2014; Hawkes et al. (2012). An extension of this concept includes when consumer decisions and related outcomes (nutritional, social, economic, environmental) are hypothesized to affect system drivers such as biophysical, environmental, technology, political, socio-cultural, and demographic ones (as in HLPE, 2017; Ericksen, 2008; Ingram, 2011; Allen and Prosperi, 2016). More specific to food security, a number of frameworks depict interactions—if not exactly feedback—between nutrition outcomes and health outcomes (Garrett, 2017; et al., 2012; Randolph et al., 2007).

Although all of the represented feedback processes are likely to be appropriate for specific purposes, the lack of consistency among the frameworks implies challenges for effective representation of these effects in agricultural systems models linking to food security outcomes. The Randolph et al. (2007) diagram is probably the most detailed and relevant of the feedback-inclusive frameworks, because it provides a more detailed representation of alternative pathways (including some described elsewhere, e.g., Kadiyala et al., 2014; Gillespie et al, 2012) linking agriculture, nutrition and health for the specific context of livestock ownership.

Not surprisingly, diagramming conventions are highly variable. Many frameworks show connecting lines (sometimes with arrows in both directions) without really indicating implied directions of causality, and only Randolph et al (2007) indicates polarities of hypothesized linkages. Diagrams are inconsistent in their depictions of hypothesized feedback processes, and in some cases it is difficult to determine what is connected to what. Language is often cryptic or a bit inconsistent among linked variables (e.g., "resources" cause "inadequate education"). The conventions used in "Causal Loop Diagramming" (e.g., Sterman, 2000) and similar hybrid diagrams that also show stocks and flows would bring a good deal of additional clarity of meaning to these diagrams (and allow them to more clearly delineate hypothesized pathways).

Many of the frameworks could also more clearly delineate so-called "model boundaries", which define what is endogenous and what is exogenous for the purposes of the (conceptual or quantitative) analysis. In many frameworks, "context" or "environment" variables appear to be assumed to be exogenous, and these encompass a vast variety of factors (political, social, cultural, knowledge, infrastructure, services, (macro)economic, climate, disease outbreak, policies, programs, conflicts, technology, food environments, legal systems, ethical values, productive assets and sometimes even food availability itself). For the purposes of many of frameworks, assuming these to be exogenous may be fine, but from a modeling perspective delineation of the model boundary is important. It is also not clear at what level many of these factors have the largest influence on outcomes. For example, the WFP framework suggests that all factors have equal impact at the community and household levels, and 'exposure to shocks and hazards' affects all levels (implied equally). This also doesn't suggest much to modelers about which effects or causal relationships are most important.

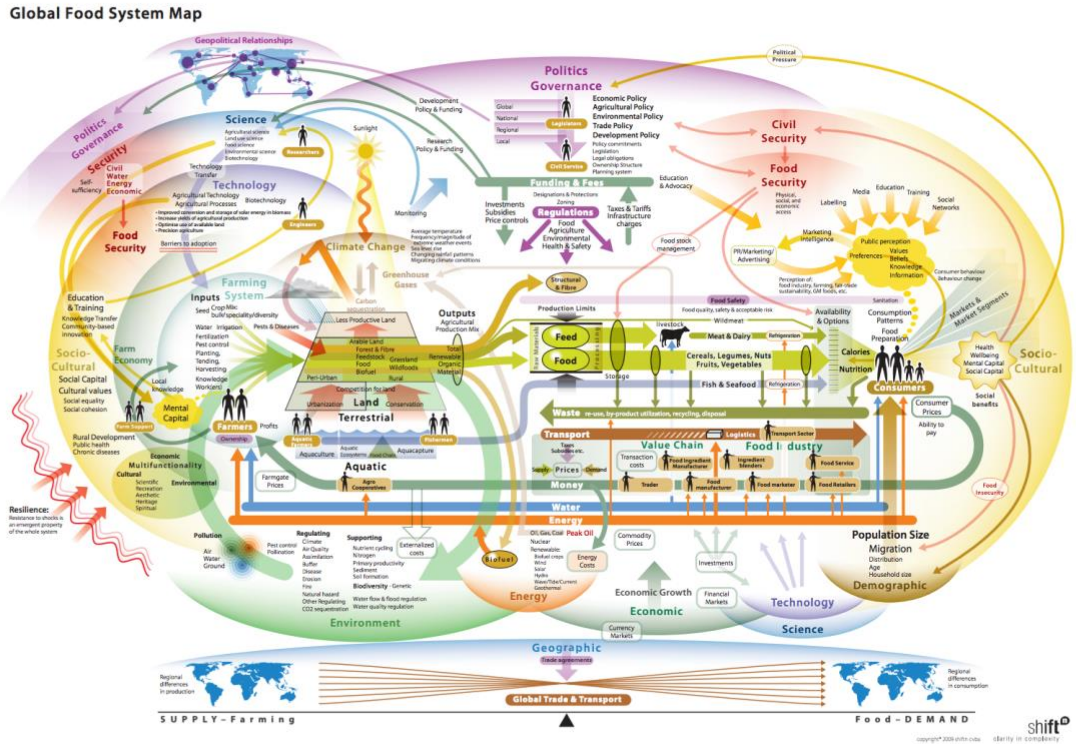

Figure 1: Global Food System Map[3]. Source: ShiftN, 2009

Discussion of food environments literature in the context of agricultural systems and food security modeling in low- and middle-income countries

A growing number of studies have more recently applied the ‘ecological system theory approach’ (e.g., Bronfenbrenner, 1989) from the human development literature to the analysis of food system outcomes (e.g., Herforth and Ahmed, 2015), which highlights the increased understanding of the importance of the food environment. . This subfield conceptualizes food acquisition and consumption choices and opportunities as being driven and shaped by what has been classified as an individual’s ‘food environment.’ This food environment is often defined—in conceptual terms at least—rather broadly as all factors affecting choices about the consumption of food. This includes factors such as the spatial density of foods on offer, food prices, product properties (e.g., quality, safety, convenience, diversity), the types of vendors offering food and “food messaging” such as advertising and promotion (HLPE, 2017). The food environment is frequently conceived

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[3] Developed by ShiftN, downloaded from: https://simapro.com/2016/developments-lca-food-data/

of a set of overlapping hierarchical influences comprising social and cultural norms and values, sectors of influence (e.g., government and media), environmental settings where food is consumed, and individual factors (e.g., demographics and knowledge) that affect food intake and physical activity levels (Herforth and Ahmed, 2015). Given the potential overlap between agricultural systems modeling and frameworks emphasizing the "Food Environment" (FE) as a key determinant of food security outcomes, we examined the current status of the literature on Food Environments to assess its potential relevance. The diversity of factors characterizing the food environment presents challenges for more complete integration of these concepts into agricultural systems models that would also represent food security outcomes.

To date, much research about food environments has been conducted in high-income regions, typically investigating potential food environment drivers of health issues resulting from over-nutrition, such as obesity. Key metrics in these contexts have included spatial analysis of the location and distance to food sources for certain populations and communities, the relative affordability of foods with respect to average incomes of consumers, inventories of food types and quality within food source outlets like stores and restaurants, or detailed breakdowns of the nutritional content of foods that are available to a population of interest. Lytle and Sokol (2017) and Ruel et al (2017) recently surveyed the literature and conclude that spatial indicators as food environment metrics dominate (such as the density of food retailers in a city center), partly due to the relative ease of obtaining these data compared to collecting detailed inventories of food outlets. Thus, much of this literature tends to emphasize settings in which food consumption decisions are made by individuals and households that do not produce substantive amounts of the food they consume—which is in contrast to the populations of agricultural producers often represented in agricultural systems models.

A recent brief by the Food Environment Working group on research gaps on food environments emphasizes the need to conduct research to apply the food environment concept in low- and middle-income countries (Turner et al 2017). Work that would emphasize elements of the food environment for households that are food producers (even if net buyers) would be most relevant for linkages to agricultural systems models, because farm production and sales patterns would be a major influence on the types of food available, distribution, relative prices and food quality. The inclusion of food security metrics into agricultural systems models in recommended in this paper, such as food consumption expenditures or the household food insecurity scale, would go some way to filling this void by linking food choices to food production in low- and middle-income settings.

Given the (incomplete) overlap between typical agricultural systems and food environment analyses it is useful to assess those variables commonly used in the food environment literature and their potential to be included in agricultural systems models (Table 1). As outlined by Lytle and Sokol (2017), the food environment has thus far been assessed through a host of survey instruments that gather variables that collectively characterize the overall food environment. For example, one common measurement tool is a 'Market Basket' questionnaire. With this, researchers estimate the overall price of a common basket of important food goods across multiple food outlets, including unit prices and quality data for a fixed set of items (e.g. milk or dairy, produce, meat etc.). Ranking the cost of a common basket for different target populations is used to assess the food environment, with lower cost baskets serving as a proxy for a better food environment overall. In contrast, agricultural systems models more frequently focus on a few specific commodities. However, market prices and agricultural output quality, of at least the commodities being modeled, are outputs from many agricultural system models that can be used to assess some components of the food environment. Given the large range of food environment variables that could be considered, this review project will only cover a subset of food environment metrics that we view as more readily able to be incorporated into agricultural systems model analyses.

The Food Environment Working group brief also outlines another useful conceptual framework for us to consider, breaking down the elements of the food environment further into an 'external' as well as a 'personal' food environment. The 'external' food environment often consists of exogenous factors that influence food acquisition and consumption, like spatial indicators of locations of food outlets, but also food prices in markets and food quality properties. The 'personal' food environment often consists of endogenous variables that are specific to household food choices, like income and expenditures on food, time constraints to obtaining and preparing food, household demographic composition and preferences. It seems possible, therefore, that some of these factors may be important, both for our primary objective of jointly modeling agricultural systems and food security indicators (like food prices or distance to markets) but also could help tease out the role of the food environment in the overall food security (and agricultural system) status of a household in a low/middle income setting. Some factors can be treated as exogenous model variables (like prices for subsistence commodities or household size) that could be adjusted to test their influence over model outcomes. They will be important in determining multiple aspects of the agricultural system behavior, calculating the food security indicator of interest and also can represent important elements of the food environment that vary across low/income settings. However, some other potential indicators, like spatial surveys or checklists of the inventories of types/qualities of foods around a given population (as exemplified by the 'food desert'[4] concept, for example), will be less relevant and would be difficult to validate with data from the low/middle income settings we are considering (rural mixed farming communities in Kenya, or commercial sheep farmers in Mexico). Thus, an incomplete accounting of the influence or role of the food environment, as captured by jointly appropriate variables, is the most likely outcome.

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[4] Food deserts are defined as geographic locations lacking access to fresh fruit, vegetables, and other healthful whole foods, usually found in impoverished areas. This is largely due to a lack of grocery stores, farmers' markets, and healthy food providers (American Nutrition Association, ANA Nutrition Digest, volume 38, number 2. http://americannutritionassociation.org/newsletter/usda-defines-food-deserts. USDA's definition is that a "low-access community," must have at least 500 people and/or at least 33 percent of the census tract's population that reside more than one mile from a supermarket or large grocery store (for rural census tracts, the distance is more than 10 miles).

Table 1. Food Environment Measurement Tools, Variables and Potential for Inclusion in Agricultural Systems Models

Food Environment Measurement Tool, Food Environment Variables Included	**Variables with HIGH Potential for Inclusion in Agricultural System Models**	**Variables with LOWER Potential (or larger difficulty) for Inclusion in Agricultural System Models**
Interviews/consumer questionnaires		
Eating habits and choices	Overall food consumption expenditures	Other aspects of food choices (preferences, tastes, knowledge)
Location of healthy food sources	Comparing on-farm production to market location for non-farm goods via market distance parameters	
Healthy food option availability	Assessment of agricultural system output of healthy food vs other commodities (ratios?)	Assessment of overall availability of healthy food in market vs. non-market outlets
Household demographics	Household size and make up (adults vs. kids, gender and food requirements and labor output etc.) as well as food consumption costs	
Market basket surveys		
Unit prices for specific food items and overall basket costs	Market prices (as both drivers of production levels of certain foods, and also as real costs of food baskets overall as a consumption parameter)	
Quality ranking for specific items	Quality of food produced – e.g. organic vs. non-organic, nutritional values/contents, 'improved varieties'	Quality of non-produced items beyond price differentials as a signal of quality
Checklists/inventory analysis		
Existence/availability of specific foods in a specific food source	Production choices made for one commodity over another and its importance to food security	Influence of household agricultural systems on total availability of important food commodities
Geographic/spatial analysis		
Distance between target population and food sources	Inclusion of non-market sources and transactions costs in overall food consumption costs	
Sales analysis		
Consumer survey of items purchased in a food source vs what is available	Total food consumption expenditures	Inclusion of food items not chosen (but available)
Nutrient/menu analysis		
Consumer survey of items purchased in a food source vs what is available	Assessment of macro/micronutrient content of foods produced/consumed	Nutritional content of available, but not consumed foods in overall environment

4. Review of existing quantitative systems models linking agricultural systems and food security

Basic concepts in agricultural systems modeling

Because non-modelers comprise one of the audiences for this working paper, we provide here a brief introduction to agricultural systems modeling, including a discussion of common general definitions, model types, and concepts related to household (economic) decision making. We noted above that we generally imply by the term 'agricultural systems model' an empirically-based[5] model that most commonly includes biophysical relationships (often at the farm or field level) sometimes complemented by economic content. An empirical model specifies mathematically a simplified representation of a specific set of real-world interactions. Often, an agricultural systems model is a *simulation model* (of one or more types) that is used for the assessment of counterfactual situations compared to a baseline or *status quo* situation—in contrast to a *statistical model* that is used primarily to determine associations between observed variables. These models are typically used to predict the impacts of management changes (such as a new crop variety or increased fertilization) or changes in context (e.g., climate or market environment) on outcomes such as crop and livestock yields or production, household incomes and consumption, environmental indicators (e.g., nutrient flows or greenhouse gas emissions) or food availability.

Agricultural systems models are typically represented by a system of equations that describes mathematically the interactions among the different elements of a specific system to be modeled. The model should have a clearly defined model boundary, which indicates the focus of the model's analytical capability and also what variables are excluded from consideration. It is also important to indicate which variables are assumed by the model to be *endogenous* (that is, with values determined by the model's calculations) or *exogenous* (with values assumed as inputs, not by the model's

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[5] There is a continuum of agricultural systems models that incorporate both empirical and theoretical components. Here we refer to a broad range that have empirical content but exclude those that are primarily or entirely theoretical.

calculations). Exogenous information used in models can include *data* (such as an assumed time series of prices for an agricultural product) or *parameter values* (often these are assumed numerical inputs into a calculation in a model equation.)

Agricultural systems models are quite diverse in terms of the agricultural activities and processes they represent (crops, livestock, fisheries, land or landscape management), although it is common for models to focus on a limited number of crop and livestock species—and sometimes their interactions. The scale analyzed can also vary, with models representing the plant, plot, enterprise, farm or household, landscape, region, country or global level. Models also differ in terms of their representation of decisions by a set of actors (often, humans assumed to be managing the system). Some models assume little or no human intervention in the system, whereas others make human decision-making a central component upon which many outcomes depend (see additional discussion below). Agricultural systems models can be *static* (analyzing a single time period) or *dynamic* (analyzing multiple time periods, typically with intertemporal linkages among outcomes).

Simulation model is a general term implying use of an empirical model to compare alternative scenarios. A simulation model can focus primarily on biophysical outcomes (such as crop yields or greenhouse gas emissions), economic decision making and outcomes (such as the choice of which crops to plant and determination of household income) or integrate the two kinds of outcomes into a single modeling framework. As an example of this latter type, the CLASSES model (Stephens et al. 2012) has detailed representation of soil nutrients, crop and livestock production, household income and assumes that a household decides how to allocate their resources (land and labor). *Optimization models* are typically used to identify what activities will best achieve a desired objective, and often have substantive economic content. An example would be a model to determine the crop mix for given farm would use to generate the largest possible farm income. Optimization models are also used to determine the equilibrium price and quantity outcomes in the markets for one or more crops based on supply and demand relationships; these are often referred to as *partial equilibrium models*[6]. Agent-based models (ABM) include explicit specification of numerous decision-making agents, whose interactions (either through direct sharing of information or through their collective impact on markets) affect outcomes for all of the agents. An example of an ABM is Wossen et al. (2018), who analyzed how multiple households with assumed different characteristics interact through crop and livestock markets to determine incomes and food availability outcomes.

Economic Models and Human Decision Making

Several distinct theoretical approaches and schools of thought about human decision making have emerged from the economics discipline that attempt to explain observed economic decision-making behavior. At present, most researchers in economics employ a variety of mathematical models to represent these theories and capture key aspects of human decision making about scarce resources. In applied settings, researchers use these mathematical representations to explain and analyze empirical data gathered about different economic phenomena, like market trading quantities and prices, or consumer spending patterns, for example.

Two of the main features of economic models of human decision making are:

1) An *objective function*, which uses a mathematical expression to represent the overall goals and preferences of the decision maker. Examples include *utility* to describe the overall level of happiness obtained by a consumer after allocating their scarce resources, or *profit* for a producer in an economic enterprise.

2) A mathematical representation of the *constraints* (or forms of *scarcity*) that the decision maker faces, for example, a limited financial budget, available land or labor resources to allocate across different activities.

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[6] "Partial equilibrium" means that only a limited number of markets (products) are considered in the analysis, whereas "general equilibrium" analyzes explicitly the interactions among all the markets in an economy.

The final piece of economic models of human decision making relates to how economic agents actually make decisions and choices about what to do with their scarce resources. The predominant theoretical paradigm in the discipline is known as *neoclassical economics.* Within this, economists assume agents are *rational actors*, and will make decisions in order to allocate resources in such a way that is *optimal* from the perspective of the *objective function* (as noted above). For example, a consumer is assumed to spend their limited income on consumption goods in order to maximize their *utility*. This process of optimizing the value of the objective function, while still respecting the constraints, is therefore known as *constrained optimization.* Thus, for consumers, they make decisions based on *constrained utility maximization,* producers will make input decisions based on *constrained profit maximization (or constrained cost minimization* if the objective function for producers is instead to limit their overall costs).

Constrained optimization can be simulated for an economic agent over a variety of important economic parameter values, like prices or income levels. If this is done, the modeler can generate an overall *demand function* for consumers, that describes what is optimal over a range of circumstances, or a *supply function,* for a producer, that indicates a set of *profit maximizing* choices that the decision maker is assumed to make when economic parameters change.

Within agricultural systems models, approaches to modeling economic factors and decision making vary widely, as initially discussed. In some instances, there is no active decision making done within the model, although the value of an economic objective function, like *profits* or *costs* or *food consumption*, can sometimes be one of the model outputs. The IMPACT model from IFPRI is one large scale example (https://www.ifpri.org/program/impact-model). In other cases, as in Stephens et al. (2012), human decision making is actively modeled, with human managers making allocation decisions over scarce resources in order to optimize the value of the relevant objective function (in the CLASSES model, the objective function is economic returns to the farmer's labor time, which is related to an overall notion of the profitability of labor on the farm).

Important alternatives exist to the neoclassical approach and are sometimes included in agricultural systems models. One overall critique from within economics as well as from other disciplines, is that the assumption of fully rational human decision making is often an unrealistic one. Alternatives to this assumption have also been employed in agricultural systems models. For example, Dobbie and Balbi (2017) employ much simpler decision-making 'heuristics' or rules of thumb when modeling the human decision making done to allocate resources for their agent-based model of Malawian smallholders. These 'heuristics' may not generate optimal outcomes for the households, with respect to the economic concepts of *utility* or *profits*. However, this may appropriate, because these outcomes may be closer to the outcomes achieved through actual decision making practices employed by individuals, particularly in light of limited information or cognitive limitations or bias in interpreting the information that is available.

Review of household model analyses of food security outcomes

We conducted a Scopus search of the search terms "Household Food Security Model" to identify the extent of existing research on food security modeling at the household level. The initial Scopus search returned 997 references that model food security at the household level in a wide variety of ways. Across this initial set of works, we found three main categories of research on food security: research at the household level, in high income settings, without agriculture; low- and middle-income settings without agriculture and low- and middle-income settings with explicit reference to agriculture. Although the first two categories are not of primary interest, these papers often discuss complex relationships between food security and other health and welfare outcomes of interest (like maternal and child health, HIV status and food security, food security in low-income urban areas etc.). Food security is either an outcome to be explained by a host of other factors (wages, demographics, poverty, living conditions or locations, for example), or as an explanatory factor for other outcomes, primarily health related (such as maternal and child nutrition, obesity). Due to the fact that these papers omit the supply side considerations of food production via the agriculture sector, they are considered outside of the scope of our review.

For our specific objectives, we focused on the third category of household food security analysis within an agricultural setting in a low- or middle-income region. Of the original 997 search results, 84 papers (detailed listing in Appendix Table A2) explicitly discussed both agriculture and food security. Despite the fact that these works explicitly mentioned both food security and agriculture, not all works examined the linkages between agriculture and food security to the same degree. The overwhelming majority of papers utilized statistical methods with cross-sectional data to assess various causal relationships between food security and an agricultural variable of interest. Furthermore, definitions of food security itself varied across these works, ranging from equating yields to food security directly, to utilizing one of the specific food security metrics we have identified as potential candidates for linking into agricultural systems research (like the Household Dietary Diversity Score, for example). Within this category, four broad categories of research were identified:

Papers that are motivated by issues of food security, but food security itself is not modeled. Food security is invoked in the motivation for the paper or in the abstract, but food security is implicitly equated to yields or increased productivity. Examples of this approach include analyses of vaccination rates for livestock (DeBruyn et al., 2017), adoption rates for drought tolerant maize varieties (Ali et al., 2017), women's empowerment programs (Burroway, 2016) and agricultural productivity (Haselow et al., 2016). No specific, validated food security metrics are used in these works.

One or more metrics representing a component of food security are analyzed as a function of a limited number of agricultural system level variables. Typically, the analysis in these papers makes use of an agricultural household survey (like an LSMS survey, for example) that has both a production and a consumption module, and possibly a distinct food security module, like HFIAS, included in the household survey. This literature most often assesses statistical relationships between different agricultural household production variables and food security status that is assessed with a specific food security indicator. Examples include the relationship between farm production diversity and household dietary diversity (Islam et al., 2018); farm size (area) and food security and food self-sufficiency (Waithaka et al., 2006) off-farm income prevalence and food expenditures (Zereyesus et al., 2017) coffee certification and both calorie and micronutrient consumption (Chiputwa and Qiam, 2016). These works typically do not model the biophysical system and think of natural capital (as measured, like soil quality, weed presence, etc.) as production inputs, measurable in levels, with no feedback or more complex system dynamics involved.

Agricultural system modeled with projection of some indicator of food security status. These works often utilize a detailed systems-oriented model of biophysical or agricultural outcomes, and the manuscript has a specific objective of analyzing agricultural system behavior and outputs from a food security perspective. These works translate agricultural system outputs, typically yields, but also potentially production of specific food characteristics, like macro- and micronutrients contained within food output, into food security metrics. As they do not typically have survey data from households on food choices, from which they could construct consumption expenditures as a food security metric, they often use a standard benchmark and compare system outputs to the benchmark. A typical benchmark used is calories produced relative to recommended level of calories per person (adult equivalent) modeled in the household (i.e., takes basic averages and ignores intra-household distribution issues and inequality). Other examples include interventions to increase animal supplementation interventions and crop-livestock farm system outputs relative to a calorie threshold per adult equivalent (Rigolot et al., 2017) and adoption of climate-smart practices and an income-based measure of food security (Shikuku et al., 2017).

More integrated biophysical or agricultural system model at the household level that considers both agricultural and food security outcomes. These works utilize full scale biophysical or agricultural system models (either household or regional level) combined with a household decision-making model to examine interplay between biophysical system and food consumption patterns, choices, vulnerabilities etc. We found nine papers of this type at the household level of analysis. The analyses in these works woud be more useful if they were morepredictive and dynamic. Leonardo et al (2018) relates agricultural productivity programs to maize self-sufficiency but also to maize sales decisions. They build an agricultural household model decision-making framework into an optimization model for maize farmers in Mozambique and use the integrated model to examine the household and national food security implications of different policies that can increase farm productivity. Whitney et al (2017) use statistical techniques but incorporate very detailed food production and nutrition data to examine the role of home gardens on both food and nutrition security in Uganda. Wineman and Crawford (2017) model farm households using a variety of techniques (linear programming, stochastic simulation) to 2050 to examine climate change impacts on farm system choices and evolution over time (crop or technology choices changing with climate, for example), with implications for calorie production on farms, and the ability of these farmers to meet their own calorie needs over time. Rigolot et al (2017) use household survey data to parameterize two farm systems and simulate the impact of climate change, also out to 2050, with divergent results for calorie production (vs. a benchmark) and incomes for small vs large farms. Dobbie and Balbi (2017) use Agent Based Modeling to simulate 'community food security,' examining how household interactions impact food security over time. Hussein et al (2017) develop a Water-Energy-Food Consumption System Dynamics model look at increased food consumption and impacts on water usage, which is the primary focus, but necessitated modeling food security (using system dynamics) as a major factor in water usage. Lázár et al (2015) modified the FAO's 'CROPWAT' model down to the household level to jointly model agriculture and poverty/food security. Louhichi et al (2014) focus on yields but use the agricultural household model framework to examine rice seed policies on the overall livelihood strategies for farmers in Sierra Leone. Finally, Wossen et al (2014) use an agent-based model representation to examine climate change adaptation strategies for households in Ghana, including the how production of calories may be changed as a result

As indicated above and in the summary tables, the papers in the fourth category are most closely related to the research question we are pursuing in this project, but they are very few in number, and often still simplify human decision making to a great degree, leading to a limited knowledge base on the 'psychometric' food security indicators and their interactions and influence within agricultural systems models.

Our review indicates that a) a large majority of papers (about 90% of them) using these key words do not fit with the criteria that we assigned for further review, b) more than half of the 84 papers we reviewed in detail are based on statistical analysis to associate a variety of variables with food security outcomes, and c) many papers do not address the stability component in any formal manner. Of the models using other than statistical methods—thus, those more likely to be consistent with our definition of an agricultural systems model—24 of 41 papers used measures of availability, especially yields or production (in quantity or calories). Eleven of the studies used some indicator of food security outcomes that was not readily categorized into availability, access or utilization. Only five of the papers using methods other than statistics employed some indicator of *food access*, and all of these were consumption amounts (physical quantities of food) or expenditures. Of the 10 papers using experienced-based food insecurity or dietary diversity indicators, all were based on statistical models, which indicates essentially no use of these indicators of food access in agricultural systems models.

It is also relevant to note that very few of these publications explicitly addressed the issue of food security from an intra-household perspective. Only three of 84 studies reviewed in detail (Appendix Table A2) mentioned or employed individual-specific metrics, and none of these used a simulation modeling approach. Islam et al. (2018) used a dietary diversity indicator specific to women as a dependent variable in a statistical analysis of the impacts of farm diversification. The RHoMIS framework (Hammond et al., 2017) includes a "gender equity indicator" but is not itself a model analysis. Ogot et al (2017) examined child anthropometric measures (a utilization indicator) in their statistical assessment of farm technology adoption.

Table 2. Summary of Food Security Outcome Indicators and Model Types for N=84 Papers Listing “Household Food Security Models” in Search Terms and Meeting Selection Criteria

Food Security Indicator	**Model Type**								
	Conceptual	**None**	**Partial Equilibrium, Optimization**	**Simulation, Biophysical**	**Simulation, Economic**	**Simulation, Integrated**	**Simulation, Other**	**Statistical**	**Total**
Availability			**13**	**2**		**9**		**21**	**45**
Caloric availability or intake			5			6		11	22
Yields or production, food available for consumption			8	2		3		10	23
Access			**2**			**3**		**23**	**28**
Consumption[7]			2			3		12	17
Food insecurity scale								3	3
Dietary diversity								8	8
Utilization						**1**		**1**	**2**
Underweight								1	1
None specified						1			1
Other[8]			**4**			**7**		**17**	**28**
Total			**19**	**2**		**20**		**62**	

Note: Totals for indicators are larger than the number of papers reviewed because some papers reported multiple indicators.

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[7] The Consumption category in this case includes both amounts of food and expenditures on food.

8 Other ‘food security’ indicators include coping strategy index, nutrient content of food, self-assessment of food scarcity (but not FIES or HFIAS), expected future food consumption, self-reported food shortages, FIVIMS, other FS indices designed by researchers in various ways (subjective, PCA), vegetable consumption per person, length of hunger periods.

Review of regional model analyses of food security outcomes

As a complement to our review of the literature on household-level model analyses of food security outcomes, we also evaluated the smaller number of regional-level analyses. We undertook a Scopus search using the terms “Regional Food Security Model”, which returned 643 possible publications. We then reviewed the abstract for each of the 643 publications and eliminated those that did not meet the specified criteria for further review: an apparent empirical model including at least one food security indicator other than crop or livestock yields or production. This left only 26 publications that were reviewed in further detail (these are listed in Appendix Table A3), which in and of itself perhaps suggests overuse of the key words “food security” in this body of literature.

As might be expected, this is a diverse group of analyses, using a variety of methods applied in different settings. For our purposes, the integration of food security indicators and the representation of dynamics are of greater importance. We assigned each of the food security indicators employed in these studies into three categories, corresponding to whether the main focus[9] was on availability, access or utilization (Table 3). Ten of the studies reviewed used variables primarily describing food availability as the principal indicator of food security. Although our intent was to screen out those publications that focused exclusively on yields or production based on the descriptions in the abstract, five of the publications employing availability measures used yield as their indicator[10]. The five other studies employing availability measures used per capita caloric availability or aggregate production (often for only some subset of grain crops).

Eight of the studies reported food security indicator measures that primarily describe the access component of food security. Three of these studies used experienced-based food security scales with questions similar to the FIES or HFIAS but only one (Cordero-

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[9] This characterization was made on the basis of those variables actually reported in the papers, which may not include all possible relevant indicators analyzed or potentially calculable.

[10] This suggests that abstracts often do not provide specific information about the indicators used to assess food security outcomes. Rather, generalized terminology is often used.

Ahiman et al., 2017) used a validated experience-based instrument (the ELSCA scale). The other studies in this category employed indicators such as aggregated food consumption (i.e., physical quantities)[11], food consumption per capita and calories per capita. Three studies employed measures that primarily focus on utilization; two used caloric intake and one used a proportion of children underweight. Perhaps surprisingly for studies indicating that they analyze food security outcomes, six of the studies reported indicators that did not obviously align with core elements of the definition of food security, using a variety of indicators (Table 3). Of these studies, Antle et al. (2014) used a household income threshold that may align with the "economically accessible" component of food access.

The integration of these food security measures into alternative modeling approaches is also of interest (Table 3). We classified models into eight categories, depending on our interpretation of their main characteristics or focus. Models using consumption (quantities of food) or caloric intake[12] tended to employ models with an economic focus (partial equilibrium or simulation models, or integrated simulation models). A number of types of models used yields or production as key indicators, but especially (and not surprisingly) those that were classified as biophysical simulation models. The three models using experience-scale indicators of food security were all *statistical* models, developed with the purpose of an improved empirical understanding the factors that contributed to food insecurity. Although in principle these relationships could be incorporated into models to simulate the impacts of changes of experiences of food insecurity, this was not done in any of these three studies.

In sum, very few of the simulation models reviewed—that is, those models that might be more consistent with the typical practice of agricultural systems analysis—used any of the three indicators we propose to measure the degree of food insecurity. Moreover, none of the analyses explicitly addressed all three dimensions of food security.

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[11] We assigned indicators based on "food consumption" variables to the access category because they often appeared consistent with the representation of "food acquired by the household", particularly in studies employing economic demand relationships.

[12] Here we note that although consumption may be considered a broader concept, in theory it is possible to derive caloric intake (or perhaps per capita caloric intake) from it, so these measures are related.

However, there is some degree of conceptual and empirical overlap between "consumption" (measured as a food security indicator by three studies) and "consumption expenditure." Measures of caloric intake (used by five studies) may also provide relevant information for food security and nutritional status assessment (particularly if converted to expenditure equivalents) even if not aligned directly with our suggested indicators.

It is our assessment that many of the studies could be more accurately described as assessing outcomes that could be described as "*potential contributions to improved food security*", rather than as more specific or appropriate indicators of "food security" as frequently conceived of and measured by nutritionists. There is a substantial body of evidence that suggests that food availability (e.g., improved yields, increased total production, or increased imports) is more likely to be a (generally) necessary but not a sufficient condition for broad-based improvement of food security outcomes. Thus, developers of empirical agricultural systems models could improve the accuracy of the descriptions of their contributions to knowledge if they exercised more caution in stating that their work represents "food security" outcomes.

Another observation regarding the models used to assess regional-level indicators of food security is the limited number that explicitly address intra-household outcomes. Only two of the 26 studies reviewed in detail included analysis disaggregated to examine outcomes of individual household members, and both of these depicted consumption or nutritional status and thus the utilization component of food security. Bakker et al. (2016) examined caloric intake by adult females and Lloyd et al. (2011) examined the number of children underweight. This suggests that as for household-level analyses, a reconsideration of the need for and methods to allow integration of intra-household outcomes is appropriate.

Another issue concerns the assessment of the stability component of food security. In principle, assessment of the stability component requires a model to represent dynamics for both a relevant *time horizon* (e.g., the length of time necessary to assess stability in light of potential shocks to the system or for the relevant impacts of, and recovery process from, a specific shock to be assessed) and a relevant *time unit of* *observation*[13]. Seven of the models reviewed would be characterized as dynamic in the sense of simulating outcomes over time[14] (Table 4), although in some cases neither the time horizon or time unit of observation is clearly stated. Models simulating annual outcomes may capture essential elements of food security challenges due to either inter-annual variation (e.g., years with good and bad harvests) or longer-term changes (e.g., to population or land use). However, when food security issues depend to a significant extent on seasonality or shorter-term shocks, annual models may not provide sufficient insights. We judged three of the publications to have models that have potential to address food security issues arising from seasonality. Akter and Basher (2014) used panel data and statistical analysis to assess determinants of food insecurity scale outcomes in Bangladesh during 2009-2010. This empirical information could be linked to agricultural systems analysis, but this was done not in their publication. Harttgen et al (2016) used statistical analysis of household-level survey data to assess impacts on caloric intake during a specific 12-month period. This could presumably be extended to future time periods with additional data. Bakker et al (2018) provide one of the better representations of food-security-relevant dynamics, simulating monthly outcomes for a period of six years (albeit with rather aggregated caloric intake indicators of food security outcomes).

A key takeaway from the assessment of models intending to assess regional food security is that relatively few of the models clearly describe a representation of dynamics relevant for analysis of the stability component of food security. (This also is consistent with the less frequent or appropriate depiction of the stability component in conceptual frameworks of food security.) In principle, developers of agricultural

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[13] Here we make the distinction between *time unit of observation* and *time step*. The time unit of observation is how frequently outcomes are generated by a dynamic model (e.g., daily, weekly, monthly, quarterly, yearly). The time step indicates how frequently model calculations are made, and in most cases it will be appropriate to calculate model outcomes more frequently than the time unit of observation to avoid what is called integration error.

[14] A number of studies report outcomes for different time periods, e.g., one current period and one future period. Although there is a temporal dimension to these studies, we did not classify them as ‘dynamic’ for the purposes of addressing the ‘stability’ component of food security.

systems models with the objective of assessing food security outcomes should be explicit about why the time horizon and time unit of observation are appropriate and consistent with their indicators of food security outcomes, particularly whether they include or ignore the stability component. It is likely that in many cases a higher degree of spatial, temporal and household-level (farm) disaggregation than that represented in the regional analysis models assessed in this review would be appropriate.

Table 3. Summary of Food Security Outcome Indicators, by Model Type, for N=26 Papers Listing “Regional Food Security Models” in Search Terms and Meeting Selection Criteria

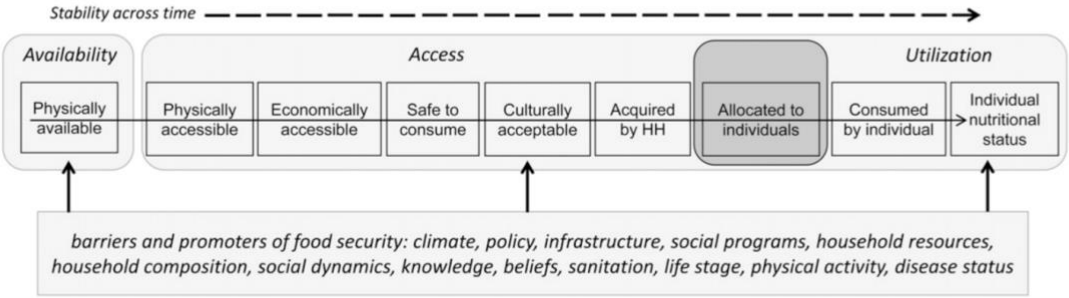
Food Security Indicator Category and Specific Indicator	Conceptual	None	Partial Equilibrium	Biophysical Simulation	Economic Simulation	Integrated Simulation	Other Simulation[a]	Statistical	Total
Availability		**1**	**1**	**4**	**1**	**2**	**1**		**10**
Aggregate Production			1				1		2
Caloric availability per capita					1	1			2
Yield per ha		1		4					5
Yield per ha; Caloric availability per capita						1			1
Access			**3**		**1**	**1**		**3**	**8**
Calories per capita in food acquired			1						1
Experience-based food (in)security scale (e.g., FIES, HFIAS)								3	3
Food consumption per capita					1	1			2
National or regional consumption			2						2
Utilization						**1**	**2**		**3**
Caloric intake							1		1
Caloric intake per capita, months with per capita caloric intake less than threshold						1			1
Percent children underweight							1		1
None of the above	**2**				**1**		**2**	**1**	**6**
CV of grain prices							1		1
Food demand = food supply	1								1
Household Income threshold					1				1
Index of supply chain coordination								1	1
None	1								1
Stylized game theory payoff							1		1
Total	**2**	**1**	**4**	**4**	**3**	**4**	**5**	**4**	

5. Review of food security indicators

The objective of this component of the project was to identify and discuss a relevant set of food security indicators at varying scales, with emphasis on households and individuals. In selecting these indicators, we were guided by the conceptual framework in Figure 2 from Jones et al. (2013) that describes the four main pillars of food insecurity: 1) food availability; 2) food access; 3) food utilization; and 4) stability. We emphasized indicators of food access in this review for several reasons. First, although food availability is certainly a cornerstone of food security, it has been recognized for decades that availability of food is not sufficient to ensure physical or economic entitlement or access to that food (Sen, 1981). National-level food availability is only weakly correlated with indicators of undernutrition, with child underweight rates, for example, varying widely at the same levels of per capita energy supplies (Haddad and Smith, 1999). Second, most low-income rural farming families depend predominantly on purchased food (vis-à-vis home-produced food) for household consumption (Global Panel, 2016). Therefore, capturing own production on farms or production at regional scales is not sufficient for understanding households' and individuals' experience of food insecurity, which entails considerable access to markets, dependence on food prices, and interactions with diverse food environments. Third, we chose not to prioritize food utilization given the challenges of assessing individual-level health and nutritional status (which strongly modifies the influence of dietary intake on nutrition and health outcomes) without hard-to-obtain clinical health and nutrition indicator data, and the considerable difficulties of ascribing a causal relationship between individual-level diet or nutrition outcomes and agricultural production indicators. Agricultural production and diet or nutrition outcomes are often conceptually "distant" from one another and there is an abundance of potential mediators along the causal pathways that present challenges for interpreting such relationships. Food access, on the other hand, captures many of these mediators (e.g., market access, household income, preferences), is more proximal to the nutrition outcomes of interest, and is therefore easier to conceptualize and model as a direct determinant of these outcomes.

We summarize several key household and individual-level indicators of food access to facilitate the delineation of those most appropriate for incorporation in agricultural systems models (Table 5). The first set of indicators is so-called experience-based indicators that rely on an individual's subjective assessment of her own or her household's recent food security status. These indicators are derived from in-depth qualitative research conducted over two decades to understand individuals' lived experiences of food insecurity (Radimer et al. 1990; Coates et al., 2006).

Figure 2. Components of Food Security and Causal Factors Relevant for Consideration of Linkages with Agricultural Systems Analyses



Source: Jones et al. (2013). What Are We Assessing When We Measure Food Security? A Compendium and Review of Current Metrics. *Advances in Nutrition*

The Household Food Security Scale Module (HFSSM) was developed for use in the United States based on this formative research, and subsequently the Household Food Insecurity Access Scale (HFIAS), Latin American and Caribbean Food Security Scale (ELCSA), the Food Insecurity Experience Scale (FIES), and the Household Hunger Scale (HHS) were developed for assessing food insecurity in a similar fashion. These tools use short questionnaires, typically administered to a household member responsible for food preparation, to assess a household's or individual's recent experience of anxiety about having enough food to eat, as well as whether they had access to an adequate quality and quantity of food. Assessing coping strategies is another approach to understanding household food access. The Coping Strategies Index (CSI) assesses the frequency of occurrence of increasingly severe coping strategies (i.e., behaviors people engage in when they cannot access enough food) to derive an overall score for each household. Dietary diversity indicators are further used as a proxy for food access.

These indicators typically provide a count of different food groups recently consumed by a household or individual. The Household Dietary Diversity Score (HDDS) and Food Consumption Score (FCS) are household-level indicators. The HDDS is primarily used as an indicator of economic access to food given its inclusion of energy-rich foods (e.g., vegetable oils and sugars), whereas the FCS, though similarly including such energy-rich food groups, also weights these food groups according to a subjective weighting scaled aimed at deriving an index more aligned with nutrient adequacy. The Infant and Young Child Dietary Diversity Score (IYCDDS) (and related Minimum Dietary Diversity (MDD) indicator), the Women's (WDDS) and Individual Dietary Diversity Score (IDDS), and the Minimum Dietary Diversity for Women (MDD-W) are all individual-level dietary diversity scores. The MDD and MDD-W have been validated as indicators of the micronutrient adequacy of diets of young children and women, respectively.

Based on our review and the information in Table 5, we recommend that agricultural systems models focus on incorporating three food access indicators: 1) food consumption expenditures, 2) experience-based food insecurity scales such as the Food Insecurity Experience Scales (FIES) or the Household Food Insecurity Access Scale (HFIAS) instruments, and 3) measures of household dietary diversity such as the Household Dietary Diversity Score (HDDS). These indicators are preferable because of the limited empirical relationship between national-level availability and individual nutritional status and because capturing own production on farms or production at regional scales is not sufficient for understanding households' and individuals' experience of food insecurity, which entails considerable access to markets, dependence on food prices, and interactions with diverse food environments (see Section 5). These recommendations acknowledge the basic validity of the approaches to measure food insecurity (see, e.g., Coates et al., 2006 and Swindale and Bilinsky, 2006). Our recommendations also align with more recent reviews of literature on food security measurement (e.g., Jones et al., 2013 and LeRoy et al. 2015). However, these indicators should be evaluated over time using the approaches like that developed by Herrera (2017) to assess more formally the robustness and adaptability components defining food security stability.

Table 5. Household- and Individual-level Indicators of Food Insecurity with a Focus on Access

Indicator	**Description**	**Empirical Availability**	**Selected Comments on Inclusion in Agricultural Systems Models**
Experience-based indicators			
Household Food Security Scale Module (HFSSM)	Measures whether household has enough food or money to meet basic food needs and on behavioral and subjective responses to that condition; 18 items (8 of which are specific to households with minors) reflect a range of severity of food insecurity experiences	The HFSSM was first administered in 1995 as a supplement to the monthly Current Population Survey (CPS) carried out by the Census Bureau to monitor unemployment and poverty in the United States. Since that time, ~45,000 households respond to the HFSSM annually as part of the CPS and the survey module has been incorporated into the National Health and Nutrition Examination Survey (NHANES) as well as data collection tools of other research efforts.	Not relevant to low- and middle-income countries (LMICs) as these data are only collected for the U.S.
Household Food Insecurity Access Scale (HFIAS)	Represents universal domains and subdomains of experiencing lack of food access; sums responses to 9 questions related to 4 domains of HFI including 4-level frequency response questions	Widely used as part of independent research efforts and evaluation of NGO food security projects. From the INDDEX Project: "The HFIAS has been included among Action Against Hunger's (ACF) core indicators in program evaluation, and has been used as one of the tools used for rapid Emergency Food Security Assessments conducted by the World Food Programme. In addition, the HFIAS is part of several household surveys (e.g., an adapted version is used in the publicly available Bangladesh Integrated Household Survey), making it useful for comparability across countries and years" (https://inddex.nutrition.tufts.edu/data4diets/indicators). The data to construct this indicator are likely not widely available in the context of nationally representative datasets.	

Indicator	**Description**	**Empirical Availability**	**Selected Comments on Inclusion in Agricultural Systems Models**
Latin American and Caribbean Food Security Scale (ELCSA)	Similar to HFIAS, though has been validated in several contexts throughout the Latin American and Caribbean region. Includes 15 questions addressed to the main household meal preparer that assess household experiences of inadequate food access in the previous 3 months resulting from a lack of resources to purchase or otherwise acquire food. Eight questions pertain to the experiences of adults in the household, and seven questions are focused on the experiences of children and adolescents under 18 years of age. Adaptations of the above description exist for different countries throughout the region. The Brazilian Household Food Insecurity Measurement Scale (EBIA) is a modification of this scale.	The ELCSA has been validated for use in various Latin American and Caribbean countries and is therefore recommended for use over the HFIAS in these contexts, though because of its regional application, data for it are not as widely available, or externally applicable as the HFIAS. The data to construct this indicator are likely not widely available in the context of nationally representative datasets.	
Experience-based indicators (cross-context comparisons)			
Food Insecurity Experience Scale (FIES)	8 questions with dichotomous responses that ask respondents to report experiences of FI of varying degrees of severity common across cultural contexts (12 mo recall)	From the INDDEX Project: "The FIES is the main indicator used for measuring progress toward achieving one of the Sustainable Development Goals, Goal 2.1, which relates to ending hunger and ensuring food access. This indicator is currently used primarily by the FAO to monitor national and global food security trends. In partnership with the FAO, the Gallup World Poll has been administering the survey to nationally representative samples in nearly 150 countries since 2014. In general, the FIES can provide information on the prevalence of varying levels of severity of insecure food access experienced by individuals (or households if administered at the household level). The FIES can also be useful in assessing prevalence of food insecurity for population-level targeting or program monitoring and evaluation; however it is not at present commonly used for this purpose" (https://inddex.nutrition.tufts.edu/data4diets/indicators).	Given its wide use globally and intended use to compare food security across diverse contexts, the FIES among all the experience-based indicators, seems perhaps most relevant for models meant to compare relationships between agricultural systems and food security broadly.

Indicator	Description	Empirical Availability	Selected Comments on Inclusion in Agricultural Systems Models
Household Hunger Scale (HHS)	Developed as a subset of questions from the HFIAS to be used for cross-context comparisons. The focus is on assessing the "quantity" dimension of food access. The scale uses the last 3 items of the HFIAS (occurrence of severe experiences of food shortage).	From the INDDEX Project: "The HHS is also included in early warning or nutrition and food security surveillance systems and can inform humanitarian response. For example, it is one of the main indicators used in the Integrated Food Security Phase Classification System (IPC), an approach developed to measure and address acute food security crises. Additionally, the United States Agency for International Development (USAID) requires that all of their Food for Peace (FFP) food assistance projects utilize HHS in both baseline and endline evaluations" (https://inddex.nutrition.tufts.edu/data4diets/indicators). The data to construct this indicator are likely not widely available in the context of nationally representative datasets.	
Coping strategies			
Coping Strategies Index (CSI)	Assesses frequency of occurrence of increasingly severe coping strategies (i.e., behaviors people engage in when they cannot access enough food). There is no universal CSI, but rather a methodology to derive locally relevant CSIs Coping strategies are organized in 4 categories: 1) dietary change; 2) short-term measures to increase household food availability; 3) short-term measures to decrease the number of people to be fed; and 4) approaches to rationing or managing the shortfall	Numerous independent research projects have used the CSI as have evaluations of NGO food security projects. The data to construct this indicator are likely not widely available in the context of nationally representative datasets, though some World Food Programme surveys have incorporated versions of the CSI into their surveys.	
Reduced CSI	A comparative (reduced) CSI using a smaller set of pre-weighted strategies	Numerous independent research projects have used the CSI as have evaluations of NGO food security projects. The data to construct this indicator are likely not widely available in the context of nationally representative datasets, though some World Food Programme surveys have incorporated versions of the CSI into their surveys.	

Indicator	Description	Empirical Availability	Selected Comments on Inclusion in Agricultural Systems Models
Dietary diversity indicators (household)			
Household Dietary Diversity Score (HDDS)	This indicator assesses quantity and quality of food access at the household level by measuring consumption of 12 food groups by any household member in the previous 24 hours: 2 food groups for staple foods; 8 food groups for micronutrient-rich foods (i.e., vegetables; fruits; meat; eggs; fish; legumes, nuts and seeds; dairy); and 3 food groups for energy-rich foods	From the INDDEX Project: "This indicator is required for all USAID Food for Peace (FFP) projects and must be collected at the projects' baseline and endline to assess the resilience of vulnerable communities and households. The FAO also uses this indicator and developed a set of guidelines for its use in different contexts" (https://inddex.nutrition.tufts.edu/data4diets/indicators). The FCS has also been used in numerous independent research projects. The data to construct this indicator are likely not widely available in the context of nationally representative datasets.	From the INDDEX Project: "This indicator is used as a proxy measure of a household's food access. Unlike measures of dietary diversity collected at the individual level, this indicator has not been validated as a proxy for nutrient adequacy. If the primary concern or research objective is to assess nutrient adequacy of the population, then dietary diversity should be collected using dietary diversity indicators at the individual, not household, level. *However, if the objective is to assess economic access to food, then the household level indicator is a more appropriate measure*. Because household dietary diversity generally increases as income increases, this indicator is sometimes used as a proxy for household socioeconomic status and is one of the indicators frequently used to assess how interventions to increase household income have affected food consumption" (https://inddex.nutrition.tufts.edu/data4diets/indicators).

Indicator	Description	Empirical Availability	Selected Comments on Inclusion in Agricultural Systems Models
Food Consumption Score (FCS)	Used by the World Food Programme to establish the prevalence of food insecurity in a country or region. The indicator combines data on dietary diversity and food frequency using 7-d recall data from Comprehensive Food Security and Vulnerability Assessments and emergency food security assessments. Respondents report on the frequency of household consumption of 8 food groups (i.e., “staples,” which include foods as diverse as maize, rice, sorghum, cassava, potatoes, millets, etc., pulses, vegetables, fruit, meat and fish, dairy products, sugar, and oil). The frequency of consumption of each food group is then multiplied by an assigned weight for each group and the resulting values are summed. This score is then recoded to a categorical variable using standard cutoff values. The assigned weights for each food group (i.e., meat, milk, and fish = 4, pulses = 3, staples = 2, vegetables and fruits = 1, sugar and oil = 0.5) were determined by a team of analysts based on the energy, protein, and micronutrient densities of each food group.	From the INDDEX Project: "The World Food Programme uses the FCS as part of its Comprehensive Food Security & Vulnerability Analysis (CFSVA) tool to assess food security and vulnerability in crisis-prone populations" (https://inddex.nutrition.tufts.edu/data4diets/indicators). The FCS has also been used in numerous independent research projects. The data to construct this indicator could be gathered from consumption/expenditure surveys or from CFSVA data.	
Dietary diversity indicators (individual)			
Infant and Young Child Dietary Diversity Score (IYCDDS)	Dietary diversity in complementary foods for children 6–23 mo (measure of micronutrient density of complementary foods). This score is used to generate the Minimum Dietary Diversity (MDD) indicator which assesses whether a child consumed 4 or more of the 7 food groups identified by this indicator.	This indicator has been used in numerous independent research projects and in evaluations of NGO food security projects. The data to construct it are largely available through Demographic and Health Survey data.	This indicator and the MDD-W are the only diet diversity indicators validated for use as proxies of nutrient adequacy of diets and as such, may be the most relevant to understanding the nutritional consequences of food insecurity. The data availability for the IYCDDS is better than for the MDD-W.

Indicator	Description	Empirical Availability	Selected Comments on Inclusion in Agricultural Systems Models
Women's (WDDS) and Individual Dietary Diversity Score (IDDS)	Individual's access to a variety of foods, a key dimension of dietary quality (meant to reflect probability of micronutrient adequacy of the diet for women of reproductive age (WDDS) or individuals > 2 yr (IDDS); 16 food groups	These indicators are newer and are beginning to be used in independent research projects and as part of evaluations of NGO food security projects. The data used to construct these indicators are likely not widely available in the context of nationally representative datasets, though efforts are underway to develop a similar indicator that would be incorporated into national data monitoring efforts.	
Minimum Dietary Diversity for Women (MDD-W) (individual)	Proxy indicator to reflect the micronutrient adequacy of women's diets; 10 food groups	This indicator is newer and is beginning to be used in independent research projects and as part of evaluations of NGO food security projects. The data used to construct this indicator currently are not widely available in the context of nationally representative datasets, though efforts are underway to develop a similar indicator that would be incorporated into national data monitoring efforts. In addition, data collection will be ramped-up significantly in the near future, with the World Gallup Poll including it and a number of countries committing to its use.	This indicator and the IYCDDS are the only diet diversity indicators validated for use as proxies of nutrient adequacy of diets and as such, may be the most relevant to understanding the nutritional consequences of food insecurity. The data availability for the IYCDDS currently is better than for the MDD-W, but the potential availability and usefulness of MDD-W may be altered by additional data collection efforts noted in the previous column.
Other household-level indicators			
Months of Inadequate Household Food Provisioning (MIHFP)	Sums the number of months in past year household did not have enough food to meet the family's needs	Used in various independent research projects and in evaluations of NGO food security projects, but likely not as common as the experience-based indicators or diet diversity indicators noted above.	
Per capita (or per adult equivalent) food expenditure	Per capita (or per adult equivalent) food expenditure within a household	Widely used in independent research projects. The data to create this indicator could be created from data from World Bank Living Standards Measurement Studies-style consumption/expenditure survey data which are primarily used to assess poverty. Such surveys are widely available throughout many LMICs (though the frequency of their implementation will vary widely)	

Indicator	Description	Empirical Availability	Selected Comments on Inclusion in Agricultural Systems Models
Percentage of household income spent on food	Percentage of household income spent on food	Likely low availability of data given challenges of collecting accurate income data in LMIC settings. Expenditure data are much more common (and likely more reliable) in these settings.	
Per capita (or per adult equivalent) energy consumption	Energy consumption per capita or per adult equivalent	Widely used in independent research projects. The data to create this indicator could be created from data from World Bank Living Standards Measurement Studies-style consumption/expenditure survey data which are primarily used to assess poverty. Such surveys are widely available throughout many LMICs (though the frequency of their implementation will vary widely)	The broader availability of data for this indicator may be one reason it is used more commonly than others to assess food security in agricultural systems models.
Per capita (or per adult equivalent consumption of energy from non-staples	Consumption of energy from non-staples per capita or per adult equivalent	The data to create this indicator could be created from data from World Bank Living Standards Measurement Studies-style consumption/expenditure survey data which are primarily used to assess poverty. Such surveys are widely available throughout many LMICs (though the frequency of their implementation will vary widely). This indicator could complement per capita energy consumption data and be calculated based on data from a comprehensive list of foods in a household consumption module. Proportion of calories consumed from non-staples would be an alternative framing of this indicator.	
Nutrient poverty	Whether a household falls below a minimum expenditure threshold for average cost of predefined food, energy, and/or nutrient basket	Not widely used, but has been used in some independent research projects. The data to create this indicator could be created from data from World Bank Living Standards Measurement Studies-style consumption/expenditure survey data which are primarily used to assess poverty. Such surveys are widely available throughout many LMICs (though the frequency of their implementation will vary widely)	

6. Priority research themes and settings for integration of food security indicators into agricultural systems models

6.1 Determinants of household food insecurity and dietary diversity

We examined the research literature to identify studies that had assessed determinants of household-level food insecurity using two experience-based food insecurity scales we recommend be incorporated into agricultural systems models: the Household Food Insecurity Access Scale (HFIAS), and the Food Insecurity Experience Scale (FIES). Experience-based food insecurity scales are meant to directly measure household- or individual-level experiences of food insecurity (Jones et al., 2013). Such scales are based on in-depth qualitative research that has identified domains of food insecurity that are consistently experienced across contexts (Coates, Frongillo, et al., 2006; Radimer et al., 1990). The HFIAS in particular was designed for use in low- and middle-income countries adapting questions from the Household Food Security Survey Module in the United States. It consists of a set of nine questions that represent universal domains of household food access (e.g., anxiety, altering food quality, and limiting food intake (Coates, Swindale, et al., 2006). The scale was designed to reflect this as a single statistical dimension of food security and has found common use as a monitoring indicator for USAID Title II food security programs. The FIES is a similar psychometric scale composed of eight questions that ask about the same experiences of FI as those in the HFIAS (Cafiero et al., 2016). The dichotomous-response options, longer recall period, and focus on categorized outcomes (i.e., mild, moderate and severe food insecurity) in part allow the FIES to be implemented as a more cross-culturally relevant assessment tool

In our examination of the research literature, we further searched for studies that assessed determinants of dietary diversity, whether at an individual-level (most commonly among young children or women), or at the level of households. Dietary diversity, the number of distinct foods or food groups in the diet, has been shown to be associated with numerous measures of household socioeconomic status that are often considered indicators of household food insecurity (Jones, et al., 2013). As a result, dietary diversity is often used as a stand-alone proxy indicator of household food insecurity.

Using Google Scholar to identify the largest range of possible studies that provide empirical evidence about the determinants of FIES/HFIAS and HDDS, we searched for studies using the following sets of search terms: “determinants of diet diversity” or “determinants of dietary diversity” (132 results); “determinants of household food security” or “determinants of household food insecurity” (842 results); “food insecurity experience scale” (268 results). Upon reviewing the titles of all 1,242 identified studies, we identified 25 relevant studies. Studies were excluded if they were not English language, were not published in a peer-reviewed index journal, included a sample population that was not easily generalizable to broader free-living populations (e.g., people living with HIV), or had very small sample sizes (generally less than 100 observations).

Studies employing the FIES were centered on global or regional analyses of data from multiple countries. This is largely due to the fact that the FIES has recently been incorporated in the Gallup World Poll, and data from this global survey are the primary source of information for the FIES at this time. Global studies examining determinants of the FIES found that the core dimensions of household socioeconomic status, namely wealth, education, and employment, were consistently inversely associated with higher household food insecurity (Frongillo et al., 2017; Grimaccia & Naccarato, 2018; Smith, Rabbitt, et al., 2017). These same studies also observed that larger numbers of children in the household, peri-urban residents of large cities (as compared to urban or rural residents), and lower social capital were all associated with a higher risk of food insecurity. Lower socioeconomic status, limited social capital, and large household sizes were similarly found to be associated with FI among regional studies from Latin America and the Caribbean and Sub-Saharan Africa (SSA) (Smith, Kassa, et al., 2017; Wambogo et al., 2018).

In contrast to the FIES, the HFIAS has primarily been used in studies within single countries of SSA, or within specific regions of individual countries. Numerous studies have used this instrument to assess household FI among people living with HIV (Hussein et al., 2018; Nagata et al., 2012; Palermo et al., 2013). Among the seven studies we identified that examined determinants of household FI using the HFIAS, five were in SSA. In the three of these studies from Ethiopia, lower monthly income, low diversity of income sources (i.e., no income from off-farm activities), larger household size, and lower levels of education were all associated with higher household FI as measured by the HFIAS (Endale et al., 2014; Megersa et al., 2014; Motbainor et al., 2016). These determining factors are highly consistent with those identified from studies using the FIES. Across all three of these studies from Ethiopia, however, low number of livestock reared, low diversity of livestock reared, or absence of livestock were also all associated with high levels of household FI. In Ethiopia, like in many low-income contexts of SSA, livestock are kept primarily as a source of wealth and income (Nyantakyi-Frimpong et al., 2018). Therefore, livestock ownership may also serve as a proxy indicator of household wealth. Two other studies from Ghana and Nigeria, respectively, further indicated the importance of household income as an important correlate of household food insecurity (Atuoye et al., 2017; Owoladeet al., 2013). Lower household income and expenditures, poorer education, lower-level employment, and larger family size were also observed as important determinants of household FI in studies from Iran and Pakistan as well (Yousaf et al., 2018).

Numerous studies have also examined associations of dietary diversity with child nutritional outcomes (Arimond & Ruel, 2004), and validation studies of the key dietary diversity indicators in common use today have examined associations of micronutrient adequacy with various combinations of foods and food groups (FANTA, 2006; Martin-Prevel et al., 2017). A much smaller set of studies has examined determinants of dietary diversity scores themselves. Among the 13 studies reviewed here, nearly all relied on food group indicators of dietary diversity, either at the household- or individual-level, while two derived a Simpson's Index (Simpson, 1949) of dietary diversity (Parappurathu et al., 2015; Venkatesh et al., 2016), and two others used a food variety score to track consumption of individual food items (Islam AHS et al., 2018; Torheim et al., 2004). Eight of the 13 studies were conducted in countries of SSA (i.e., Kenya, Benin, Tanzania, Zambia, Mali, Nigeria, Malawi; Ayenew et al., 2018; Kiboi et al., 2017; Kumar et al., 2015; Marinda et al., 2018; Mitchodigni et al., 2017; Ochieng et al., 2017; Snapp &

Fisher, 2015; Torheim, et al., 2004), while the remainder were conducted in India and Bangladesh. Among those from SSA, again, socioeconomic indicators related to education, employment, income, food expenditures, and assets were among the most salient predictors of dietary diversity. Not surprisingly, child age was also positively associated with diet diversity in several studies (Marinda, et al., 2018; Mitchodigni, et al., 2017; Torheim, et al., 2004). As children age out of infancy, the diversity, amount, and range of consistencies of foods they can consume increases, thus allowing for more diverse diets. Several studies also found that households headed by women, or those with the women as income earners also had higher diet diversity (Kumar, et al., 2015; Ochieng, et al., 2017). These findings align with prior evidence suggesting that greater decision-making responsibility in the hands of women within households is associated with more positive diet and nutritional outcomes (Herforth A et al., 2012). Many of these same sociodemographic factors were identified as associated with higher dietary diversity in India and Bangladesh as well including literacy, per-capita income, women's self-efficacy and spousal support (Chinnadurai et al., 2016; Nguyen et al., 2017; Parappurathu, et al., 2015; Venkatesh, et al., 2016).

Yet, in addition these sociodemographic factors, land ownership was also positively associated with more diverse diets in Kenya (Kiboi, et al., 2017), Tanzania (Ochieng, et al., 2017), and India (Chinnadurai, et al., 2016), while in Zambia, the inverse relationship was observed (Kumar, et al., 2015). The authors of the Zambia study posited that this finding may have been due to households with larger land holdings cultivating cash crops (e.g., maize and cotton) that did not directly contribute to the diets of farming households. Furthermore, agricultural production diversity was associated with more diverse diets in Benin, Mali, Zambia, Nigeria, India and Bangladesh. These findings are supported by a larger set of studies that have been previously reviewed that have found a consistent positive, albeit small in magnitude, association between on-farm crop species richness and household-level dietary diversity (Jones, 2017). In some contexts, this relationship may be stronger among households with low on-farm diversity (Sibhatu et al., 2015). The study from Nigeria reviewed here observed that agricultural production diversity was especially strongly associated with dietary diversity among households in higher income quantiles (Ayenew, et al., 2018). Importantly, several studies, including those examining production diversity, have also found that access to markets (i.e., proximity to nearby markets) is positively associated with dietary diversity as well (Bellon et al., 2016; Jones , 2016; Koppmair et al., 2017; Kumar, et al., 2015; Sibhatu, et al., 2015; Snapp & Fisher, 2015). However, it is clear that agricultural production diversity and market-orientation of farms are not contradictory trends, and rather are often complementary (Jones, 2016). Experimental studies intervening to diversify homestead food production through kitchen gardens and the rearing of poultry and micro-livestock have observed corroborating findings that more diversified home agricultural production leads to more diverse diets and higher consumption of targeted fruits, vegetables and animal-source foods (Olney et al., 2015).

In total, these studies suggest the paramount importance of household socioeconomic status (i.e., wealth, education, and employment) in shaping food insecurity (Table 6). Increasing women's status within households (i.e., control over income and decision-making, bolstered by spousal and familial support), in particular, may be crucial for improving food security on the margins. Larger numbers of children within families may be related both to socioeconomic and women's status, as large families have to distribute income among more household members, and the burden of childcare commonly falls to women who must trade-off time and labor to childcare with other activities (including income-generating activities; Mcguire & Popkin, 1990). Among rural farming households, larger land sizes, more diverse agricultural production (which are themselves positively correlated), and access to markets are also predominant household-level factors that likely serve as important determinants of household FI across contexts.

Table 6. Summary of Relationship between Determinants and Household-Level Food Security Indicators and Their Likely Role in Agricultural Systems Models

Determinant of Food Security	FIES	HFIAS	Dietary Diversity[a]	Comment on Relevance for Agricultural Systems Models
Model Outputs Used as Food Security Determinants[b]				
Wealth (Assets)	-			Some models currently include this and most household models could in principle.
Income		-		Some models currently include this and most household models could in principle.
Income source diversity		-		Some models currently include this and most household models could in principle.
Food consumption expenditures			+	Some models currently include this and most household models could in principle.
Model Components Used as Food Security Determinants[b]				
Women's decision-making[c]	-	-	+	Could be included as a component of decision making about production and consumption in agricultural systems models.
Livestock ownership		-		Some models currently include this (e.g., CLASSES) and most household models could in principle.
Diversity of livestock species owned		-		Some models currently include this and most household models could in principle.
Agricultural production diversity			+	Some models currently include this (e.g., CLASSES) and most household models could in principle to some degree.
Employment	-		+	Some models currently include this (e.g., CLASSES) and most household models could in principle.
Model Inputs Used as Food Security Determinants[b]				
Education	-	-	+	Could be included as exogenous determinant of food security.
Number of Children	+			Could be included as exogenous determinant of food security. Although agricultural systems outcomes could affect number of children, most models do not include this as an endogenous variable.
Household Size	+	+		Could be included as exogenous determinant of food security. Although agricultural systems outcomes could affect household size, most models do not include this as an endogenous variable.

Determinant of Food Security	**FIES**	**HFIAS**	**Dietary Diversity**[a]	**Comment on Relevance for Agricultural Systems Models**
Social capital	-			Could be included as exogenous determinant of food security. Although agricultural systems outcomes could affect social capital, most models do not include this as an endogenous variable.
Land ownership			+	Could be included as exogenous determinant of food security. Although agricultural systems outcomes could affect land ownership most models do not include this as an endogenous variable.
Literacy			+	Could be included as exogenous determinant of food security. Although agricultural systems outcomes could affect literacy, most models do not include this as an endogenous variable.
Proximity to markets			+	Could be included as exogenous determinant of decisions affecting food security.
Peri-urban resident	+			Could be included as exogenous determinant of decisions affecting food security.

[a] Measures of dietary diversity include food group indicators, Simpson's Index and food variety score.
[b] Here we define a "model output" as a variable that is calculated by the model rather than using an assumed value. A model output thus derives from computations made by the model (often referred to as "endogenous" in the model structure). "Model inputs" are values that are assumed in order to make the calculations (thus are "exogenous" based on model structure). "Model components" include parts of a model that could be either assumed as inputs (thus, are exogenous) or based on decisions that are represented in the model (endogenous). For example, the number of livestock could be assumed as an (exogenous) input or determined by decision making (endogenous).
[C] This includes female-headed households, women's control over income and decision-making, women's self-efficacy, spousal support and related measures.

Note: Signs are interpreted as partial impacts of an increase in the value of the determinant variable on the food security indicators, holding other factors constant (i.e., consistent with link polarity in SD models). For example, an increase in wealth causes a reduction in the degree of FIES (i.e., an improvement). An increase in the number of children causes an increase in the degree of FIES (i.e., a deterioration). Thus, + signs for FIES and HFIAS indicators indicate worsening, + for Dietary Diversity is an improvement.
Note: The summary comments above assess a) whether the determinant is currently directly represented in agricultural systems models, and b) whether the determinant is likely to be affected by agricultural system outcomes (production, income, labor allocation, etc.) The importance of each of the determinants for agricultural systems models would in principle depend on the magnitude of the impact and the degree of difficulty in incorporating into models and the degree of effort required for empirical representation.

6.2. Agricultural systems models and consumption expenditures: a summary of approaches

Agricultural systems models treat human decision making in a variety of ways, some of which are more conducive than others to connecting agricultural system model outcomes to one of our proposed indicators of food security, food consumption expenditures. Various ways in which the interface between agricultural systems and consumption expenditures are discussed in the literature are summarized below, along with exemplar papers of the type and methodological approach.

The Agricultural Household Model (Singh et al., 1986), emerging from the agricultural and development economics literature in the 1980s, represents one approach to the question of how to integrate agricultural production and consumption into a combined model. However, the AHM often lacks in sophistication on the agricultural system side, although it does include a modeling framework for determining consumption expenditures via a household consumption demand function, oftentimes for food specifically, given the low-income, rural settings where it is usually employed.

A 2003 review of the AHM by Ed Taylor and Irma Adelman outlines the various questions and settings where the AHM has been employed. From the beginning, the AHM has been concerned with the impact of agricultural policy on food production and consumption, arising in part out of the counterintuitive evidence that government pricing policies did not necessarily incentivize more food production in low income areas with large numbers of food insecure people. The AHM employs a utility-maximization framework for the household, with consumption expenditures emerging from the constrained household optimization model as a set of demand functions, both for market and non-market consumption goods (as well as production inputs). A 1994 edited volume by Joachim von Braun and Eileen Kennedy at IFPRI highlights the use of the AHM more specifically to examine agricultural commercialization policies, comparing different agricultural production systems in the context of their impact on food security, and the likely impact of commercialization schemes, particularly emphasizing cash/non-food crops, on overall household ability to guarantee food consumption. It covers research that is more detailed on the agricultural systems side than is typical for the literature on the AHM overall, since the concern in the volume is with a switch to commercial, market-oriented production, thus an enterprise shift that can be compared in its food consumption expenditure outcomes, via changes in food demand functions that are derived from the AHM. But besides management or enterprise mix, there is little in these models of the biophysical information that characterizes many agricultural systems models published in the literature.

Radchenko and Corral (2018) is another recent work using a version of the AHM to link agricultural production and crop portfolio choice (cash vs. food cropping) to food expenditures, using semi-parametric methods. The likelihood of choosing to grow cash crops, based on biophysical as well as local market data, is used as an input into modeling food expenditure, although it does not specifically model food expenditures as a structured demand function and has limited biophysical information. The approach is possible in this instance because the authors have direct access to food expenditure data that they can try to model and link to production data, rather than constructing food expenditure demand as a function of household preferences and utility functions, as well as production inputs, prices etc.

At a basic level, many agricultural systems models, which are typically more detailed than the AHM in their structures for the biophysical dimensions of agriculture, simply parameterize human decision making, in the sense that analysis of agricultural systems in these instances often compares a set of farm management practices to another, and then reports system outputs (such as production or income) . One of these outcomes might be food that is available for consumption (physical quantities), which is sometimes passively compared to a self-sufficiency benchmark. The model behavior does not necessarily change if the consumption benchmark is not met, indicating a lack of active decision-making about consumption.

An example of this approach can be seen in a recent *Agricultural Systems* paper by Rigolot et al (2017) that contrasts two typical multiple- agricultural-enterprise systems and their implications for food production, and food security, defined as calorie production as a percentage of a fixed caloric benchmark. There is no feedback in this model from the household food security calculations and outcomes back to the underlying biophysical model, but consumption can be compared across enterprise systems. But an assumption is made about the equivalency between food production and consumption, and consumption expenditures are not truly modeled, as food consumed by the household is assumed to come out of own production, with surplus food produced sold to provide additional income. Since there is no feedback between the economic submodule and the production module, food consumption expenditures will not emerge as a model variable or outcome, as shortfalls do not trigger additional food expenditures in the market.

Other joint models include human decision-making more directly in the model behavior during simulation, by introducing potential simple decision rules about minimum consumption levels as a fixed constraint in the system. The modeled household will then manage system resources in such a way to guarantee a particular (fixed) level of consumption, either by producing it themselves, or purchasing from the market in the case of a shortfall. This introduces feedback from the economic decision-making about consumption expenditures back into the biophysical system, and allows some degree of active choice about consumption expenditures in terms of re-allocating system resources.

An example of a combined model in this mode can be seen in an Agricultural Systems paper by Thornton, Galvin and Boone (2003) based on developing a joint ecological and socio-economic model of agro-pastoralist households in northern Tanzania. The researchers combine the Savanna ecological model designed for pastoral areas in Kenya, with a simplified household model that links the biophysical outputs from the Savanna model to assessments of household welfare for the pastoralists themselves. The Savanna model combines a model of forage production, with a model of grazing for forage by livestock, tracking vegetation quantity, quality, density, soil dynamics, water dynamics, environmental shocks like climate change and fires, removal of forage by the livestock, and the herd dynamics that result from changes in forage. If a consumption shortfall occurs, then the household must take action to purchase food to address the gap, and food consumption expenditures can be observed in the model. The food consumption expenditures are thus either zero, in the case of sufficient own production, or some positive amount required to finance the gap, which is financed through selling livestock, drawing down cash reserves, deferring some types of consumption and some additional techniques. Consumption expenditures are thus not modeled like a demand function per se, one that is sensitive to food prices and income levels, and potentially flexible when the household is faced with trade-offs in obtaining food from own production and the market, vs. consuming other goods. There is a subsistence constraint, and if it is met, then expenditures will not occur.

A third approach involves incorporating the AHM into an agricultural systems model more explicitly, where household decision-making is modeled via constrained household utility maximization, but household demand for consumption expenditures is flexible and sensitive to internal and external relative market and/or shadow prices, incomes, preferences, etc. A recent paper by Leonardo et. al (2018) on the impact of extensification and intensification of agriculture in Mozambique and maize production comes somewhat close to this approach, in that there is an assumed decision maker in the household that chooses to either maximize total farm gross margins or maize sales, and then examines the consequences of the different objective functions on farm production and resource allocation. It assumes food self-sufficiency as a constraint, however, and food expenditures are thus not an outcome of the model.

A more extensive search may reveal the full incorporation of an AHM into an agricultural systems model, however as Leonardo et al point out, this would necessitate some information to use to parameterize the underlying utility function which may not be available. Other potential complications on a full interface between agricultural systems models that capture biophysical processes, feedback and interactions potentially in a continuous way, would have to be fed to the household, with assumptions made about how much of this information is observable to the farmer, what are the farmer's/household's intertemporal optimization/risk preferences, both in terms of the biophysical system as well as over prices, and yields which are more typically included in an intertemporal version of the AHM. Modeling food expenditures as an additional outcome of an agricultural systems model will thus involve use of an AHM to insert an overarching decision-making framework about allocation of farm resources to optimize over household utility, which would then determine yields, labor allocation, cash expenditures etc. to produce agricultural output, and home-produced food and then, eventually, food expenditures in the case of insufficient home production. Interesting questions might arise about whether a household might have a flexible level of consumption out of home production, based on changes in market prices for food or other goods. A demand system that comes out of an AHM would have a structural way to introduce variation in prices (and potentially other elements of both production and consumption) into food demand overall, with an implied impact on consumption expenditures if consumption out of own production decreases. Any model output suggesting relationships like this would have to be validated with observed data.

6.3. Identify priority opportunities for linkages between agricultural systems models and food security outcomes

The discussion in Sections 6.1 and 6.2 above are central to the ability to specify quantitative relationships between the outputs typical of (or relatively easily derived from) agricultural systems models and food security outcomes such as consumption expenditures, FIES and HDDS and to understand priorities for needed future research. This section builds upon this and previous information to describe our assessment of priority opportunities. We acknowledge that these are somewhat speculative in the sense that they are not based on more formal analysis of the costs, benefits or importance of the opportunities, and that such an analysis could be helpful to further refine our judgments. We discuss separately three sets of opportunities, as follows:

Settings for which there is an opportunity for low cost for inclusion of food security indicators (perhaps due to both the structure of extant models and data to support empirical linkages to food security outcomes). Our review above suggests that the potential for low-cost implementation of food security indicators in agricultural systems models may be rather narrow at present. This is because relatively few of the existing model analyses currently include any of our three recommended indicators directly—the most common being some form of consumption (food amounts, expenditures, or calories)—and model analyses were nearly universally vague at best about defining what pattern of indicators describes the stability component of food security. This suggests that the lowest-cost means of analyzing food-security in agricultural systems models likely will be improvements in existing models to the representation of food consumption, aligning definitions more closely with the indicators and categories (e.g., the food access dimension) suggested herein, and applying the kinds of stability metrics described by Herrera (2017). Note that this suggests that dynamic models (i.e., rather than partial equilibrium ones) with appropriate temporal resolution (perhaps monthly at minimum), time horizon (likely more than one year) and analyzing households individually would tend to be more appropriate for incorporating this type of analysis. In the few situations where empirical data are available to link the outcomes of agricultural systems model to experienced-based food insecurity indicators and household dietary diversity scales, these could generally be incorporated into existing dynamic agricultural systems models at low cost. We illustrate this with our proof-of-concept household and regional model analyses in the next section (albeit assuming many of the necessary empirical relationships).

Settings or linkages for which additional empirical evidence (data) is needed to integrate food security indicators. This appears to be the far more common context for the agricultural systems models we have reviewed. Many models appear to have been developed without reference to specific food security indicators as defined by human nutritionists (e.g., these previous analyses assume production equates to food security) or with only a limited subset (e.g., various indicators of consumption). In general, agricultural systems model analyses tend to focus on the outcomes with closer linkages to the "*availability*" component of food security (which is understandable given their biophysical focus), whereas we suggest a focus on indicators of *food access*. In very few cases is the empirical evidence to link the biophysical outcomes (and economic outcomes, such as income) to experience-based food insecurity scales and household dietary diversity, although as we illustrate below, the extant literature on their determinants suggests some common patterns with regard to outcomes such as income.

Greater efforts at data collection to facilitate the analysis of the determinants of these outcomes—especially those biophysical and economic outcomes common in agricultural systems models—is urgently needed if these indicators are to be systematically represented in agricultural systems models.

Efforts such as RHoMIS[15] (Hammond et al. 2017) that collect experience-based food insecurity and dietary diversity information provide a framework for collection of these data, which in principle would best be undertaken as one of the components of the empirical evidence base underlying model development. This would not seem to involve a great deal of additional effort or cost if model development is based on field survey work collecting related information such as yields, income consumption, etc. However, the appropriate degree of temporal granularity may suggest that multiple rounds of such data collection are appropriate for dynamic model development. There is undoubtedly much work to be done to determine appropriate analytical (statistical) techniques of analysis to develop appropriate theoretical foundations and functional forms linking determinants to indicators, but even more simplistic empirical relationships may be useful as this body of work is explored and expanded. As more empirical evidence linking outputs from agricultural systems models to indicators such as FIES and HDDS, it may be possible to use relationships from other (reasonably similar) settings in a more stylized manner.

Themes (events, influences or interventions) that would likely have a large impact on food security outcomes related to agricultural systems dynamics. As noted earlier, it would be possible (and also necessary) to undertake a more formal assessment to determine which "events, influences or interventions" amenable to analyses by agricultural systems models have the largest degree of impact (either positive or negative) on food security outcomes. Moreover, the empirical evidence base to date allows relatively limited inferences about which of the determinants of food security indicators has the largest positive impact in defined contexts. This also may be relevant to the development of model analyses—particularly those with the objective of

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[15] We believe that the RHoMIS approach has great potential to facilitate the incorporation of food security indicators into agricultural systems models. However, it is worth noting that the methods used for the collection of these indicators depart in potentially important ways from those used in validating the original indicators. For example, The HDDS departs from standard practice by using long-term (and seasonal) recall rather than 24-hour recall as in the validated scale. We thus recommend caution in the use of these indicators generated through RHoMIS pending additional validation work. We include a short additional discussion in Appendix 2.

determining which system modifications result in the largest improvements in food security. Thus, we use both professional judgment and a review of the previous modeling work to suggest priority areas.

One set of priorities relates to shocks that could negatively affect production, incomes or both for populations of agricultural households that are likely to be more vulnerable due to less favored environments or smaller initial resource endowments. Some obvious sources of these shocks include weather events (drought, flooding), plant or animal disease outbreaks, major agricultural or trade policy changes, decreased access to agricultural market outlets and household-specific idiosyncratic shocks (e.g., loss of a family member's labor). Weather events (especially changes in rainfall) were a common motivation for analysis of food security among the household-level and regional-level publications reviewed.

Longer-term processes that could negatively affect food security include climate change (both effects of changes in rainfall and temperature distribution and evaluation of adaptation strategies), land use change, land fragmentation (or consolidation policies), decreases in biodiversity, natural resource degradation and demographic shifts (migration to urban areas). Many of the reviewed studies were motivated by a desire to understand the food security implications of these processes.

It is also possible to envision events, influences or outcomes that would result in temporary or enduring improvements in food security. Thus, many of the publications we reviewed focused on such influences as farm technology adoption (for management of crops, livestock, trees, nutrients, water and soils), participation in new (or more commercialized) agricultural value chains, diversification of agricultural production. In some cases, the analyses focused on assessment of policies or programs designed to facilitate these changes.

A number of regional studies focused on what might be termed "visioning" studies that used simulation modeling of stakeholder-generated scenarios to compare food security (and other) outcomes under alternative futures (e.g., Springmann et al., 2016). These studies are less concerned with the assessment of specific shocks or programmatic implementation than influencing the strategic direction for country and regional food and agricultural sector development. To the extent that such longer-term studies consider food security outcomes, there are opportunities for improvement of their representations, although the lengthy time horizon may imply changes in the empirical nature of the relationships between determinants and food-security outcomes.

Analysis of Strategic Priorities and Transformative Changes to Food Systems. In the next section, we describe proof-of-concept analyses of common shocks (e.g., reduced crop yields) or policy interventions (e.g., supporting the adoption of productivity-enhancing technology by larger-scale producers). These align with common applications of agricultural systems models—particularly those with economic content, and many models would allow the assessment of a large number of similar impacts or interventions. However, there are potential applications of agricultural systems models that assess the food security impacts of transformative changes to food systems and provide a more strategic assessment of intervention (and research) priorities.

As an example of the former, it would be possible with certain types of models at both the household and regional scales to evaluate the impacts of large-scale changes in crop and livestock production patterns[16]--perhaps to align them more closely with recommendations for healthy or environmentally sustainable diets. Agricultural systems models incorporating these assumptions could then be used to assess the impacts on food security indicators and other outcomes of interest, such as incomes, relative prices (for market models), nutrient flows and other environmental indicators.

A number of modeling approaches (particularly the System Dynamics approach used in our proof-of-concept analyses) have as their principal objective the identification of key "leverage points" (strategies) that can result in the largest sustained improvement in outcomes of interest. Used in this manner, at least some agricultural systems model could be used to assess strategic approaches that provide the largest sustained improvement in food security outcomes—or that best prevent or mitigate the impact of shocks affecting food security. Typically, these would be done in a comparative manner

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[16] Typically, imposing this sort of large-scale structural change would require "over-riding" the underlying economic decision-making logic (at the household level) or market responses (at the regional level) and might also require substantive consideration of the capacity of input production and post-production supply chains.

that assess a number of possible strategies. At a very general level, these could include comparisons of production-related decisions (improved crop varieties, irrigation, crop-livestock mix), consumption-related decisions (educational efforts to effect behavioral change, e.g., “demand generation”, Monterrosa, 2018) or supply chain interventions (such as improved transportation or storage). Analyses could also focus on decisions about one of these general areas, such as which “climate-smart” production practices (e.g., Thornton et al., 2017) have the largest benefit in terms of food security. This approach can also be used to assess the trade-offs between food security and other outcomes (such as income or environmental impact).

Agricultural systems models could also be used to assess which information is most needed to assess and improve food security outcomes, through the application of uncertainty and sensitivity analyses. It is common in many models that some uncertainties about assumptions have a limited effect on simulated outcomes, whereas the results are quite sensitive to other assumptions. This suggests that efforts be focused on better understanding of assumptions (information) the results in large uncertainties of outcomes (such as food security). Thus, in addition to assessing specific interventions or modifications, agricultural systems models incorporating food security indicators can be highly useful for priority-setting.

7. Proof-of-concept case analysis for integration of food security indicators into agricultural systems models

We determined that it would be appropriate to modify two existing models: one at the household level (CLASSES, Stephens et al., 2012) and one at the regional level (Mexico Sheep Sector Model (MSSM), Parsons and Nicholson, 2017) to include relevant linkages to food security indictors. The CLASSES model represents a single household in the Kenyan highlights producing maize and potentially dairy cows, forage and tea. The MSSM represents sheep supply and demand for all of Mexico with production disaggregated by farm types and regions. We also decided that that because this is a "proof of concept" exercise, the models used would not need to a) allow the assessment of a wide range of possible impacts of shocks or interventions on food security indicators, or b) have fully-developed empirical evidence to support the linkages between their predicted bio-economic outcomes and food security indicators (although clearly more is preferred). Thus, the purpose is to provide a template for integration of food security indicators in agricultural systems models and demonstrate the usefulness of this integration—with appropriate emphasis on dynamic stability of outcomes.

Incorporation of the Food Security Indicators into the CLASSES Model

The CLASSES model is a bio-economic system dynamics model of a small mixed enterprise farming system, calibrated with survey data on smallholder producers managing a portfolio of maize, livestock, Napier grass and tea in Kenya. Several key agricultural and economic systems are represented, including tracking dynamic behavior of key soil nutrients and organic matter stocks, crop production for three important representative food, forage and cash crops, livestock investment and management for dairy production, and an overall decision-making structure that allows for the household to continually adjust land and labor resources towards their highest returns on the farm. The primary causal loops for the CLASSES model include those for consumption, cash accumulation and soil organic matter dynamics (Figure 3). The figure illustrates the principal stocks (accumulations such as cash or soil organic matter) with boxes, and inflows and outflows that affect the value of the stocks as double arrows with a valve (two triangles). Arrows illustrate causal linkages between variables and their hypothesized sign (or polarity). (A "+" sign indicates that a change in variable at the beginning of the arrow will cause a change in the same direction for the variable the arrow points to; a "-" sign indicates a change in the opposite direction. Thus, an *increase* in household available cash is hypothesized to cause an *increase* in the value of grain consumption, but an *increase* in the value of grain consumption results in a *decrease* in the consumption shortfall.) Feedback loops are indicated as collections of causal linkages (e.g., household cash available is part of a loop comprising a series of connected causal linkages that also includes a livestock purchases, livestock numbers, milk production, milk cash value and cash inflow). Because it was designed to evaluate longer-term poverty-trap dynamics, the model uses quarterly time units, but the numerical integration calculations are done 16 times per quarter (i.e., time step of 0.0625).

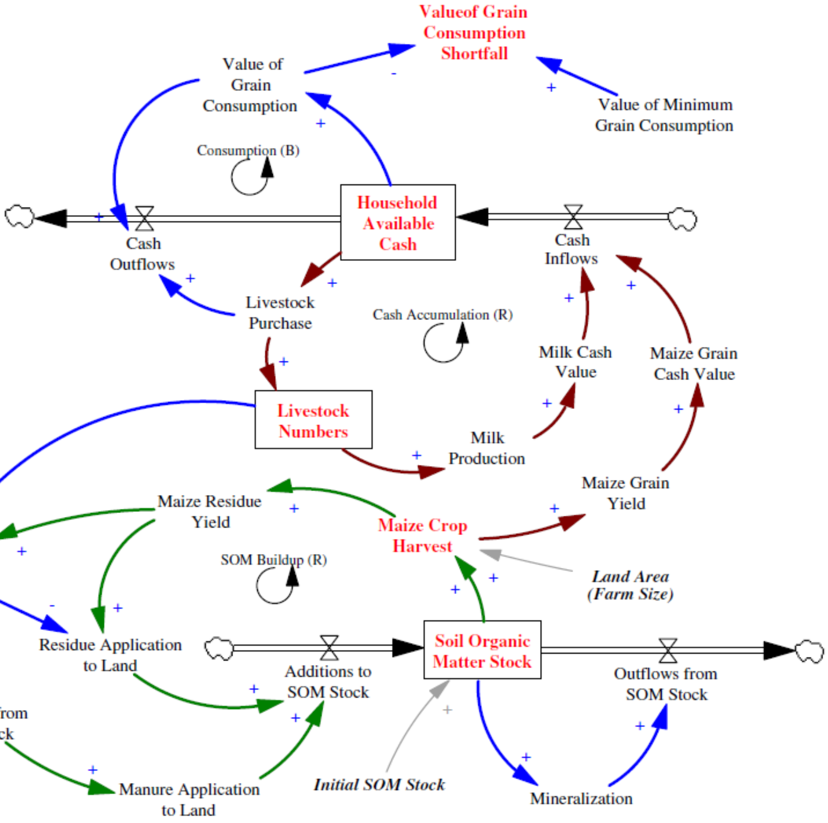

Figure 3: Primary causal relationships within the CLASSES model between the economic and biophysical systems on smallholder Kenyan farms. Source: Stephens et al. (2012).

In order to highlight the relationships between agricultural system dynamics and potential food security (as represented by selected indicators) for the smallholders represented by the CLASSES model, we examined the impact of a negative maize yield shock, with households experiencing two consecutive maize crop failures. We imposed this yield shock on two distinct types of households to further examine the impact of various scale factors on both agricultural system and food security outcomes. The first household has 0.5 ha in land, 6 family members (2 adult laborers) and relatively low levels of human and financial capital. The second household has 1 ha, 5 family members (3 adult laborers) and higher levels of human and financial capital (Table 7). For this analysis, the model is simulated for a time horizon of seven years, long enough to examine initial behavioral patterns before the yield shock and the adjustment process afterwards.

In previous analysis done with the CLASSES model, farm size proved important in determining whether households could avoid low-equilibrium welfare level poverty traps, with bifurcated trends in yields, biophysical capital, income and wealth accumulation between small and poor vs. larger, wealthier farms (Stephens et. al, 2012). Many of these same factors are associated with food security, as evidenced by the literature review, thus examining the impact of a significant agricultural shock on these two household types can help further highlight the additional welfare impacts with respect to food consumption patterns that are likely attendant with other indicators of household well-being. Further, a supply shock for an agricultural subsistence producer represents the direct shock to the food availability dimension of food security that is also the main focus of much of the literature on agriculture and food security.

Table 7: Key Household Parameters for Two Representative Household Types for Analyses with the CLASSES Model

Model Assumption	Household 1	Household 2
Land area, ha[a]	0.5	1.0
Adult laborers, persons	2	3
Children, persons	4	2
Total household size, persons	6	5
Initial education level, years	4	10
Initial Savings[b], KSh	6,960	14,690
Initial FIES Score[c]	2	4
Initial HDDS Score[c]	3	5
Expenditures required for consumption of minimum recommended quantities of food, KSh/quarter	6,960	7,345
Recommended minimum food consumption, kg/quarter		
Cereals	360	380
Animal Source	72	76
Oils	72	76
Fruits & Vegetables	54	57
Other	36	38

[a] All land is assumed to be planted to maize (no tea or Napier) and there are no livestock for the entire simulation period of 28 quarters. Note that livestock could be purchased but sufficient cash is not accumulated to do so. We further assume no use of inorganic fertilizer for both households.

[b] Variable *AccumSurplus* in CLASSES. Calculated based on the minimum food consumption expenditures per quarter times 1 for Household 1 and 2 for Household 2.

[C] Although a "Base Score" value for this indicator is assumed to be the same for the two households, household characteristics that affect the value of the initial FIES and HDDS scores in the model differ for the two households.

We modified the CLASSES model to incorporate three separate food security indicators: food consumption expenditures, the FIES and the HDDS. For food consumption expenditures, following one basic approach in existing literature (e.g., Wossen et al 2018), consumption functions were added for five food item categories with assumed values of minimum recommended consumption, mean price and income elasticity of per capita consumption (Table 8).

Table 8: Demand Parameters Assumed for Analyses with the CLASSES Model

Characteristic	Cereals	Animal Source	Oils	Fruits & Vegetables	Other
Minimum recommended consumption, kg/person/quarter[a]	100	20	20	15	10
Price of food, KSh/kg	8.33[b]	25	10	25	10
Income Elasticity of per-capita consumption[c]	0.2	0.8	0.3	0.5	0.5

[a] Value assumed for adults. Children are assumed to consume 40% of this value, on average.

[b] Can vary depending on whether household is net buyer (higher value) or net seller (value above).

[c] Income elasticity values are adapted in a stylized manner from Wossen et. al (2018)

The consumption functions are based on the net income to the household relative to the total expenditure required for the household to consume the minimum recommended quantities of each of the five food items. Net income (NI) is defined as the net inflows per quarter of cash from sales, wages, off-farm labor earnings, remittances, minus any cash outlays for production (hired in labor, production inputs).

Household consumption of each food item (kg/quarter) is thus calculated for three situations:

1) household income is currently adequate to consume at or above the minimum recommended amount of each food item;
2) household income is not adequate to consume the minimum recommended amount of each food item, but savings are available to support consumption at the minimum recommended level;
3) household income is not adequate to consume the minimum recommended amount of each food item and no savings are available.

The applicable amount of each food item to be consumed is calculated conditional on the situation above, and total food expenditures (in KSh/quarter) are calculated using consumption and prices.

The specific consumption functions follow a basic log-linear form, with net income (NI) influencing the household's ability to consume relative to a minimum standard, as shown below:

$$\begin{gathered}\textit{HH Consumption of Food Item } f = \\ (\textit{Min. Recommended HH Consumption of Food Item } f) \times \\ \{NI + \textit{Allowable Savings Draw}/ERCMRA\}^{\textit{Income Elasticity for Food Item } f},\end{gathered}$$

where the *Allowable Savings Draw* (ASD) indicates the amount that can be withdrawn from the household's savings. In the first two scenarios described above, the household has sufficient cash resources to afford the minimum required consumption bundle (ERCMRA), either through quarterly net income, or some combination of net income and drawing down savings.

If net income falls below the amount needed to afford the minimum required consumption bundle (the ERCMRA), but the household also does not have savings on hand, existing resources are allocated with priority given first to cereals and oils, and then equally across the remaining three food categories with remaining cash resources. This is reflective of likely prioritization given by severely food insecure households, but relative weights have been chosen arbitrarily, and could be adjusted if there were known rankings and priority weights for a specific set of households.

Amounts of actual consumption by the HH for each of the five food items also is calculated as discussed reported above. In addition to actual consumption amounts, we calculated the number of food items for which the household consumed more than 25% of the minimum recommended amount, and this was indicated as a proxy for the total number of food groups consumed (and thus, one measure of dietary diversity).

The FIES and HDDS indicators were also included, with linkages added to additional important determinants taken from the literature (like numbers of dependent children, for example). These indicators are the summed responses to a series of yes/no questions about food security, resulting in integer valued scores. We thus used discrete thresholds for linking agricultural system model variables to the FIES and HDDS food security metrics, starting with an assumed set of base values, to which discrete additions or subtractions from the Base value are made when agricultural system model values pass the thresholds.

For example, the FIES score is calculated as:

FIES Score = Base FIES Score + f(Wealth, NI, Education, HH Size, Children, Off-farm Income),

Where the elements of the *f( )* are as follows:

Wealth Effect = -1 if Wealth > 25,000 KSh, 0 otherwise

where

Wealth = Value of Land at 10000 KSh/ha + AccumSurplus + CashAvailable

NI Effect = -1 if NI > 5000 KSh/quarter, 0 otherwise

Off-Farm Income Effect = 1 if income from off-farm labor earnings > 2500 KSh/quarter, 0 otherwise

HH Size Effect = 1 if HH Size > 4, 0 otherwise

Children Effect = +1 if Children >2, 0 otherwise

Education Effect = -1 if Education years > 6, 0 otherwise

Note that a higher FIES score implies a higher degree of food insecurity, so positive values in the above indicate a deterioration of food security status and negative values imply and improvement.

The HDDS is calculated as:

HDDS = Base HDDS + f(Land Area, Education, Food Consumption Expenditures, Off-Farm Employment),

Where the elements of the *f( )* are as follows:

Off-Farm Income Effect = 1 if income from off-farm labor earnings > 5000 KSh/quarter, 0 otherwise

Land Area Effect = +1 if Land area > 1 ha, 0 otherwise

*Food Consumption Expenditures Effect = +1 if FCE > 1.5*ERCMRA, -1 if FCE > 0.8*ERCMRA, and 0 otherwise*

$$\underline{\text{Education Effect}} = +1 \text{ if Education years} > 10, 0 \text{ otherwise}$$

These are arbitrary both in their formulation and their specific numerical values but attempt to capture in a stylized manner the kinds of effects that would be relevant to consider. Further consideration of how to collect and analyze data on the determinants of FIES and HDDS will be essential for more appropriate empirical analyses.

The dynamic patterns for the three food security indicators across both household types, along with several other key characteristics of food consumption, are shown below (Figures 4 to 7). The maize yield shock is imposed on the model in quarter 8, leading to both short-term and long-term changes from the baseline (i.e. no yield shock) scenarios shown for both households.

The yield shock has a substantive effect (Figure 4) on food consumption expenditures, as well as the cost of the minimum required consumption bundle (the ERCMRA as described above). Several important features stand out. First, intuitively, the yield shock negatively impacts overall food consumption expenditures, but not to the same degree for both households. Household 1 experiences a deeper and more prolonged drop in food expenditures, remaining below the minimum required for 5 quarters, while expenditures for Household 2 drop below the minimum threshold later and rebound more quickly. Household 2 starts the simulation with more than double the level of savings of Household 1 and is able to use these resources to better maintain access to food from markets, despite the production shortfall.

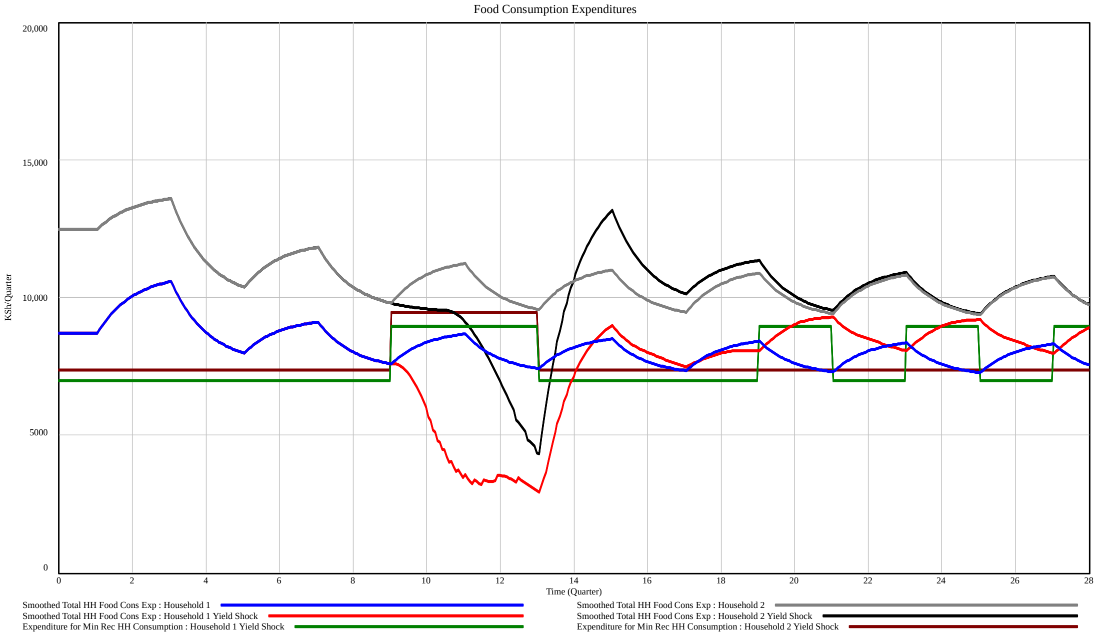

Figure 4. Household Food Consumption Expenditures (KSh/Quarter), Two Household Types, With and Without Yield Shock, Compared to Expenditure Required to Consume Minimum Recommended Amount

Also of note are the differential effects long term on food expenditures between the households. Household 2 eventually returns to expenditure patterns of its baseline, but Household 1 displays different levels of expenditures after the yield shock, with food consumption expenditures rising over baseline. This is not necessarily an indicator of greater food security, however, as the cost of the minimum bundle begins to fluctuate as the household switches between being a net seller of maize (with lower market prices) and a net buyer, which raises the overall cost of the consumption bundle. Thus, expenditures rise along with costs, as the shock appears to permanently diminish the household's capacity to produce enough maize for minimum consumption—in part because it now in engages in off-farm labor—and it makes up the maize production shortfall with purchases in the market.

All three elements of food security represented in the model are affected by the shock. Food availability is affected (due to lower production), as well as access (through higher prices for households that transition into net buyers and have more reliance on market purchases). Stability of food security, as measured by food consumption expenditures, is not achieved, but particularly for Household 1. Both households experience fluctuations in food expenditures, due to variable seasonal levels of production of the main staple crop between short and long rains seasons, as modeled in CLASSES. However, these fluctuations remain above the minimum required expenditures for Household 2, operating on a larger farm, with more savings to compensate for any shortfalls. Both households appear to adapt to the shock to food consumption expenditures, but this adaptation is incomplete for Household 1, as it leads to a series of shortfalls below the minimum expenditures required.

The HDDS reflects the number of 12 food items consumed by any member of the household during the previous 24 hours. The initial values for the two households differ based on food consumption expenditures and land area and attempt to capture differences in HDDS due to different resource bases. In the absence of a shock, Household 1 experiences an increase in quarter 1 based on food consumption expenditures higher than a threshold value, but a reduction in HDDS when food consumption expenditures decrease after quarter 2. The increase in HDDS in quarter 24 is due to educational attainment. Household 2 experiences fluctuations in HDDS due to seasonal variations in food consumption expenditures. The yield shock lowers the HDDS by 1 for Household 1 during quarters 9 to 13 due to lower food consumption expenditures. However, Household 1 also does not experience the improvement in HDDS that occurs at quarter 24 in scenario without the yield shock, because lower income prevents educational attainment. Similar to the impact of the yield shock on Household 1, Household 2 experiences a decrease of 1 unit during quarters 9 to 13, but also an *improvement* in the value of the HDDS from quarters 21 to 23. This increase is due to additional food consumption expenditures made possible by maize yields sufficient to meet the consumption expenditure threshold. Maize yields after the shock are larger than they would have been in the absence of the yield shock for the three subsequent harvests due to soil nutrient dynamics and because nutrients were not harvested in the form of maize during the yield shock. These higher yields support higher income and additional cash savings accumulation, which supports higher consumption levels in the quarters immediately after the shock.

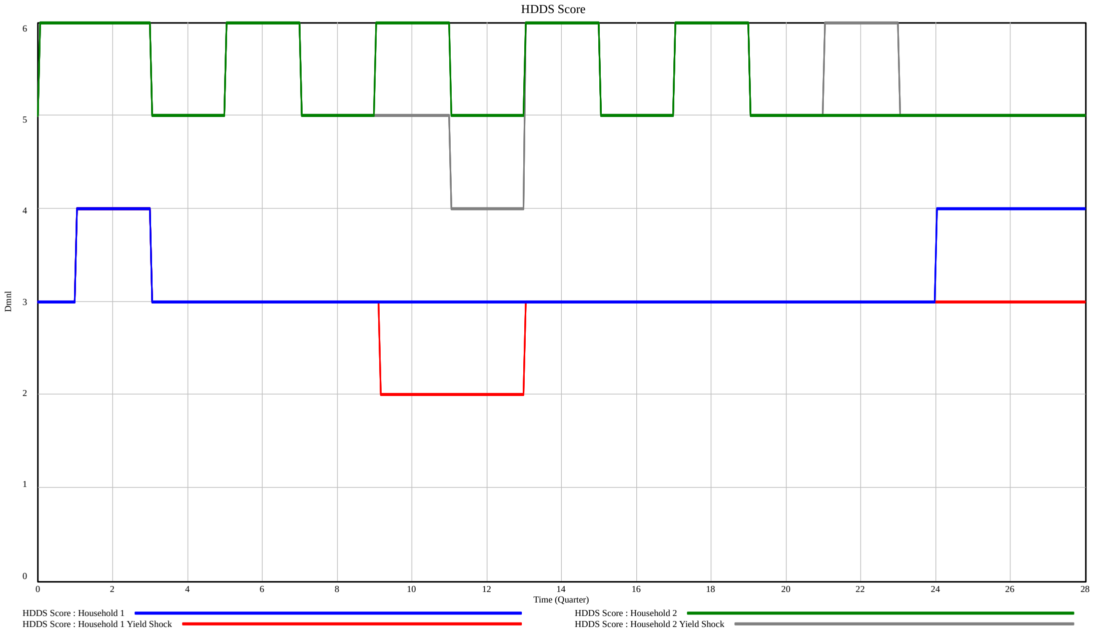

Figure 5. HDDS Score, Two Household Types, With and Without Yield Shock

The pattern of behavior for the indicator of the count of food groups consumed which underlies the HDDS can also be assessed. For this analysis we use a simplified approach based on only five categories of food groups rather than the 12 in the HDDS survey[17]. We assess the baseline number of these food groups for which consumption is more than 25% of the minimum required, and then the impacts of the shock. In the absence of the shock, both households are able to consume all five food groups well above minimum levels. The impact of the shock is quite different for the two households (Figure 6). Both households experience declines in the numbers of food groups consumed, however the reduction in food group variety is only prolonged for Household 1, dropping to just one food group (cereals) consumed above the 25% level a year after the shock and remaining below 5 for a year. Household 2 consumes only one food group at less than 25% (animal source foods) and only for one quarter. Both households recover from the shock and increase variety back to initial levels. If this indicator is

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[17] We acknowledge that the count values are not entirely consistent between our analysis of the HDDS that is more comprehensive and the analysis of the counts for these five food categories but for illustrative purposes this may be acceptable.

designed more stringently (with 50% thresholds rather than 25% of the minimum), Household 1 consumes only 1 food group (cereals) at levels above the minimum for twice as long (4 quarters rather than 2) and experiences brief periods during quarter 11 when even cereals consumption is below 50% of the minimum requirement (not shown).

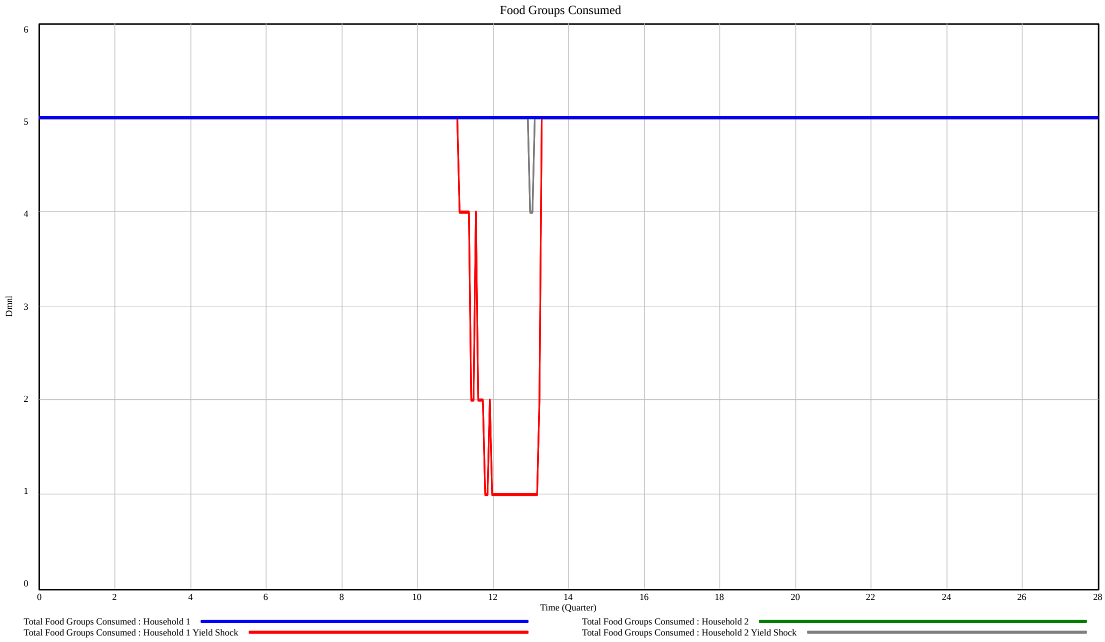


Figure 6. Number of Food Items for which Consumed Amount is > 25% of Minimum Recommended, Two Household Types, With and Without Yield Shock

The baseline pattern and impact of a yield shock can also be assessed for the FIES score. Starting from a lower based value of the FIES, Household 2 experiences two step increases in the FIES at quarter 9 and quarter 11, with an overall increase compared to the scenario without the yield shock during quarters 9 to 13. After quarter 13, the impact of the shock has passed and the FIES score returns to the initial value (Figure 7). The value for Household 2 equals that of Household 1 during quarters 11 and 12, despite the higher initial resources. The pattern of the FIES score over time and the response to the yield shock are different for Household 1 than for Household 2. Prior to the shock at quarter 8, the FIES score increases and decreases due to wealth effects and drops by a value of one at quarter 8 because of an accumulation of education by the household head. The yield shock results in an initial increase in FIES score during quarters 9 to 12 due to the loss of income from maize sales, but off-farm employment reaches the assumed threshold in quarter 11, which decreases the FIES score by 1 point. Once maize yields return to normal in quarter 12, Household 1 experiences fluctuations in FIES due to seasonal off-farm labor (which is assumed to decrease the FIES value), which results in a lower overall average FIES value after quarter 13. Thus, for Household 1 the pattern of the FIES score is permanently altered (but actually improved) as a result of long-term changes in agricultural production and labor allocation decisions brought on by the yield shock.

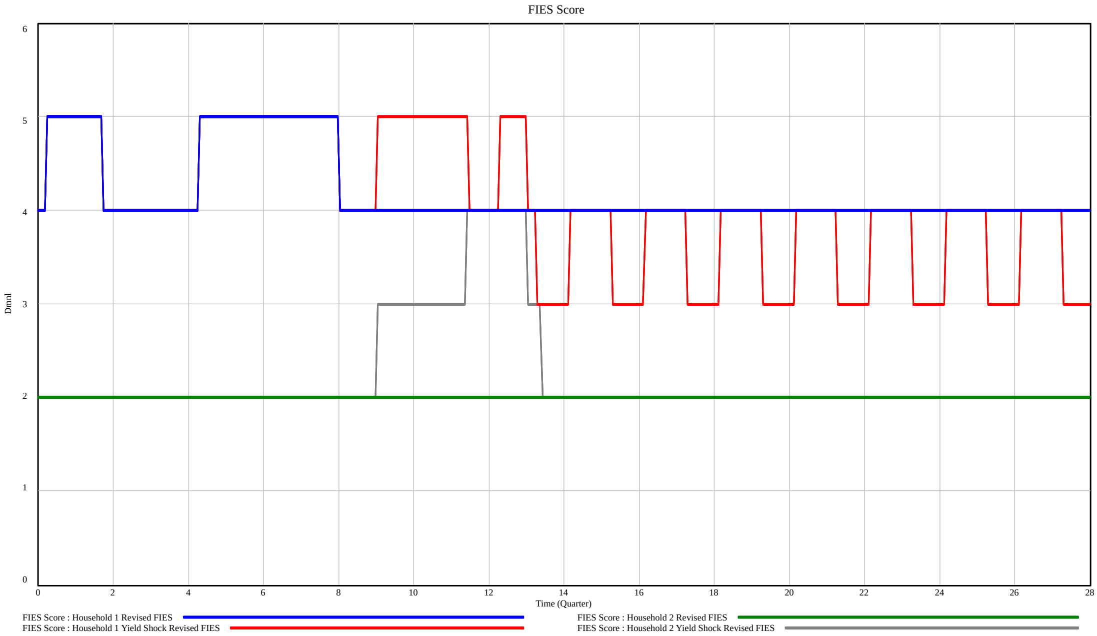


Figure 7. FIES Score, Two Household Types, With and Without Yield Shock

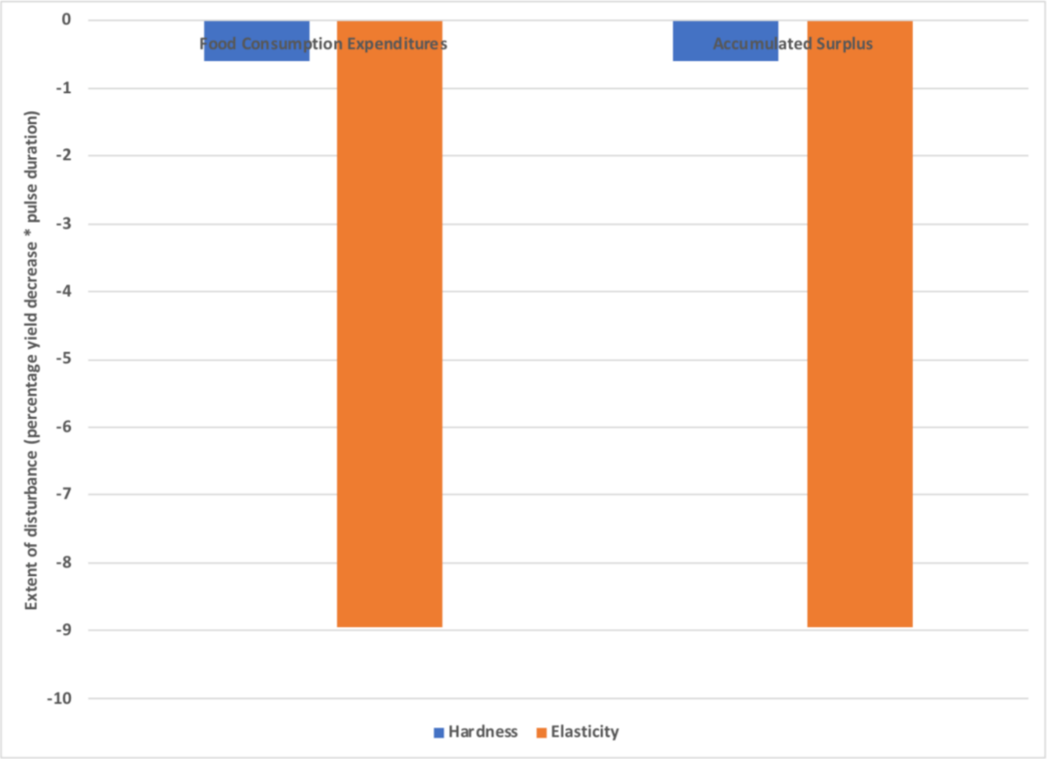
In addition to the analyses described by Figures 4 to Figure 7, we calculated two of the resilience metrices proposed by Herrera (2017), hardness and elasticity. For illustration purposes, we only ran the resilience analyses for the lower-resource Household 1. Hardness describes the ability of the system represented in the CLASSES model to withstand a disturbance without presenting a change in the performance of the food security indicators, in this case, of household food consumption expenditures and total accumulated surplus. The larger the hardness value, the larger the disturbance needed to produce a change in behavior of the two indicators. Elasticity, on the other hand, describes the ability of the system to withstand a disturbance without changing to a different steady state. The more elastic the system, the larger the disturbance it can absorb without shifting into an alternate regime.

We calculated the resilience measure for two types of disturbances: climatic (yield shock) and economic (price shock). Disturbance for the purpose of our analyses refers to a) in the case of a climatic shock to the multiplication of the yield change and duration of the yield change and b) in the case of an economic shock to the multiplication of maize price changes and the duration of the price change. For the climatic disturbances, we ran Monte Carlo analyses where we varied yield changes in a range between -25% and -99% and a pulse duration (duration of yield change) in a range between 2 to 10 quarters. For the economic disturbances, we varied the magnitude of maize price change from -5% to -50% and the duration of the price change from 2 to 10 quarters.

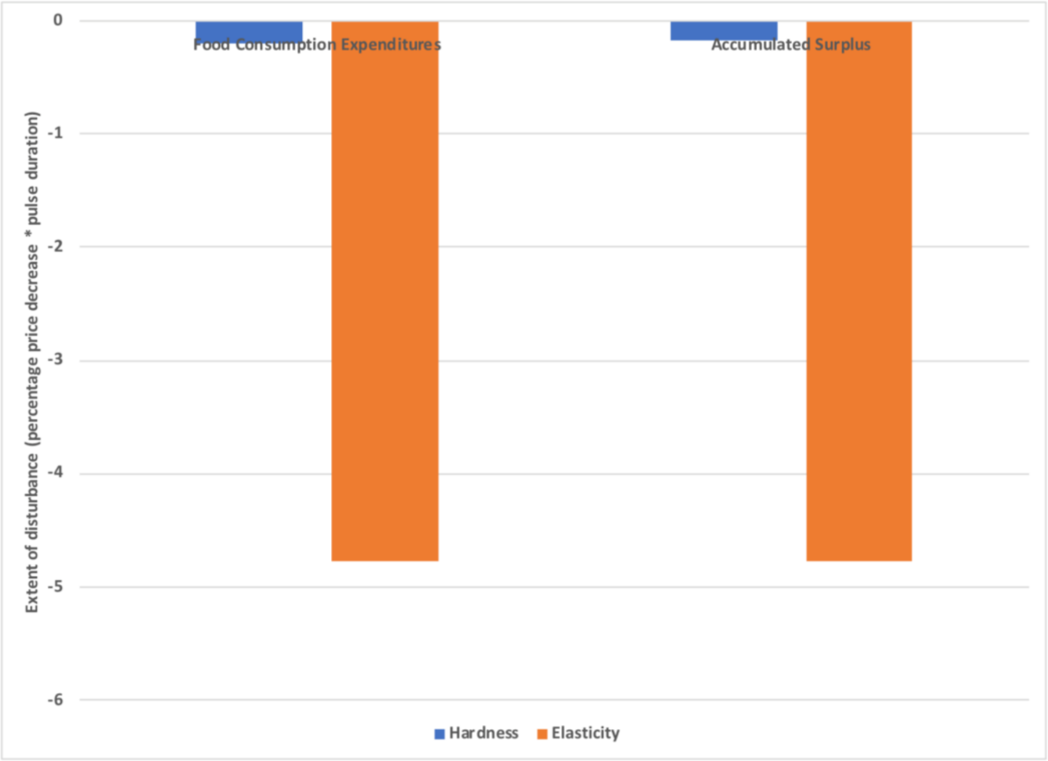
Our analysis summarizes results for hardness and elasticity for the household food consumption expenditures and an underlying determinant, total accumulated cash savings held by the household (Figure 8). The hardness metric denotes the maximum disturbance that the indicator can tolerate before its behavior changes significantly (within a 5% confidence bound) with respect to its behavior in the absence of a disturbance. It can be thought of as the maximum disturbance before the system bends. The elasticity metric describes the maximum disturbance the indicators can tolerate before they never recover to their reference behavior (within a 5% confidence bound). It can be thought of as the maximum disturbance before the system breaks.

Both the smoothed total household food consumption expenditure and the accumulated cash savings deviate significantly (5% confidence bound) from the reference behavior at very small disturbances (very low values of the hardness metrices, Figure 8). (The values in the figure are negative because a larger shock has a larger negative impact on the value of food consumption expenditures and accumulated savings). However, both indicators are able to recover from very large disturbances (very high values of the elasticity metrics). Given the parameter ranges we used for the Monte Carlo simulations, both parameters were able to recover from the maximum disturbance (99% reduction in yield and 50% reduction in maize price). Therefore, while the system seems to be very susceptible to disturbances, it shows at the same time a fairly high degree of adaptability. This is true for both household types analyzed, but the adaptability is associated with different behavioral responses. Household 2 is able to recover from the shock and return to the previous pattern of production. Household 1 makes a permanent shift in the allocation of its labor, devoting more labor to off-farm employment and less labor to its maize production. We did not find any significant differences in resilience between household food consumption expenditures and accumulated cash savings, which suggests the importance of liquid wealth as a factor mitigating the impacts of shocks affecting food security.

Figure 8. Resilience Analysis for Food Security Indicators and Yield (8a) or Maize Price (8b) Disturbances in CLASSES



a)



b)

Overall, including a variety of food security metrics into the CLASSES model highlights different potential impacts of the yield shock on food security. For example, food expenditures fall, particularly for the smaller, poorer household, but the household is still able to maintain a degree of dietary diversity. The experience of food insecurity, as measured by FIES, is also dynamic, and demonstrating continuous representations of food security in this way highlights new potential questions about how households manage food security across time. Existing literature about the role of seasonality in agriculture (and food security), highlights variation across seasons, but is typically measured discretely, given the cost associated with fielding household surveys multiple times during the year. Patterns shown here, if calibrated better with known elasticities and empirical relationships, can fill in gaps from survey data alone, and also prompt new questions about household validation of variable food security experiences, or their ability to plan, foresee them, compensate for them.

Incorporation of the Food Security Indicators into the Mexico Sheep Sector Model

The Mexico Sheep Sector Model (MSSM) comprises a stock-flow-feedback structure originally designed to represent the potential for nonlinear (or counterintuitive) responses to current livestock policy instruments and productivity-enhancing technological change (Parsons and Nicholson, 2017)[18]. The model represents sheep and sheep meat markets in Mexico, but also includes trade linkages because of the importance of imported sheep meat in Mexican consumption. The production sector is represented by two different regions (Yucatán and Other), rather than household decision-making as is represented in CLASSES. Although Yucatán only produces a small proportion of Mexico's sheep meat, it is represented separately to illustrate impacts on a region with a large proportion of small producers, relatively distant from main consumption centers. Each region has two different types of producers: commercial or *tras patio* (Parsons et al., 2006). Commercial producers tend to be larger scale, have better access to capital, have good market access and are often owned by individuals for whom agriculture is not the principal economic activity. *Tras patio*, or backyard, producers are smaller scale, often have a limited investment in sheep production other than animals, (that is, they do not typically invest in housing or equipment) have poorer market access and are owned by individuals who earn a significant portion of household cash income from agriculture. The differences in producer characteristics are assumed to influence the costs of production and prices received for live animals. Consistent with available evidence, demand for sheep meat is centered on a single market in Mexico City. As in the commodity models developed by Meadows (1970) and Sterman (2000), inventories of sheep meat are assumed to influence the price of sheep meat, which in turn influences both sales (quantity demanded) and sheep meat imports. The model uses a monthly time unit of observation, a time step of 0.125 months, and is typically simulated for a period of 10 years. A diagrammatic representation of the model shows the major stocks, flows and feedbacks (Figure 9). Similar to Figure 3, the figure illustrates the principal stocks (accumulations such as animal numbers or meat inventories) with boxes, and inflows and outflows that affect the value of the stocks as

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[18] This section draws upon the discussion in Parsons and Nicholson (2017) to a large extent.

double arrows with a valve (two triangles). Arrows illustrate causal linkages between variables.

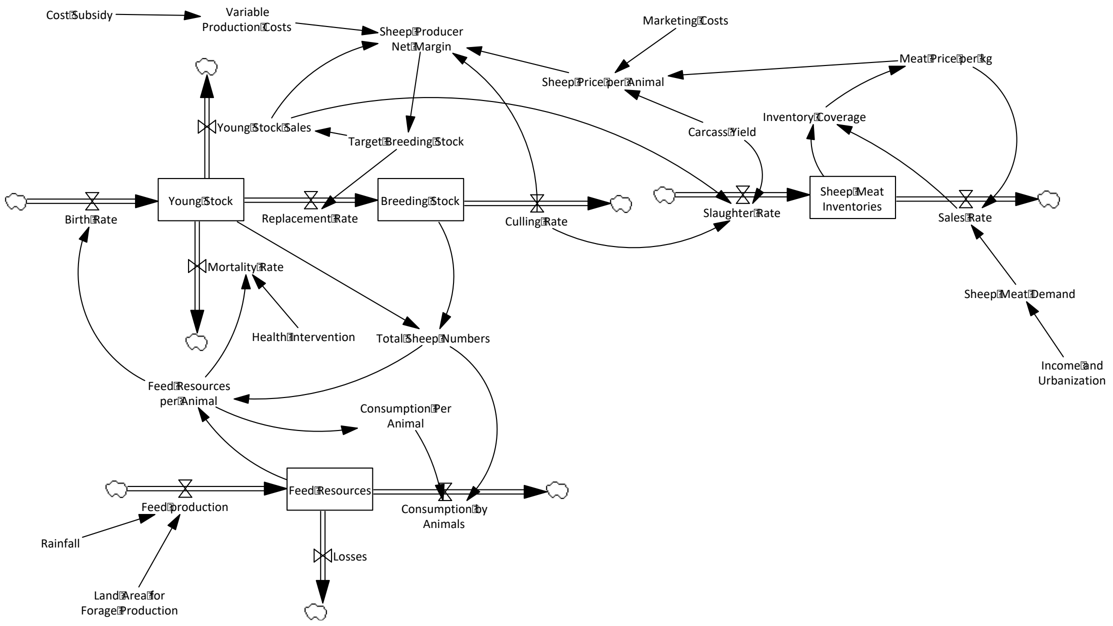

Figure 9. Simplified Representation of Principal Stocks, Flows and Feedback Processes in the Mexico Sheep Sector Model (MSSM)

The MSSM was based on market and trade data available through 2007. It has previously been used to explore the impact on production, prices and producer income of various productivity-enhancing interventions and cost subsidies provided to larger-scale producers in the context of various assumptions about demand growth rates (no growth, constant growth, slowing growth). In this analysis, we examine the impacts of two scenarios on food security indicators for smallholder (*tras patio*) producers in Yucatán relative to a Baseline. The two scenarios both include an annual demand growth rate of 1.5% for three years after an initialization year, but constant demand thereafter. In one scenario, commercial producers (but not *tras patio* producers) in both regions are offered a cash payment from the government equal to 30% of their variable costs beginning after the first year, which is similar to programs offered by state governments in Mexico in the mid-2000s, and which incentivizes additional sheep production. These two scenarios are compared to a dynamic equilibrium scenario (which assumes stable production, prices and incomes) that serves as a reference.

A representation of each of the three recommended food security indicators was incorporated into the MSSM. Because this is a model at regional scale, we ignore household-specific characteristics and focus on only one driver of food security outcomes, regional producer income, for only one subset of producers, *tras patio* producers in Yucatán. (Commercial producers generally represent a socio-economic demographic for whom food security would not be a major issue.) We assumed a given level of non-sheep income for *tras patio* producers in aggregate, although we also allowed for (but did not use) in the model structure for the possibility that non-sheep income could decrease if producers devoted additional resources to sheep production[19]. We used proportional changes in income from the reference scenario (dynamic equilibrium) to calculate proportional changes in food security indicators assuming constant-elasticity responses. The basic formulation for computing these proportional changes is:

$$\%\Delta FSI = \%\Delta INC \cdot \eta^{FSI}$$

Where FSI indicates the food security indicator, INC indicates total regional income (from sheep production and non-sheep activities) for *tras patio* producers, and η is an elasticity value that relates the average level of FSI for Yucatán *tras patio* producers with respect to income. This formulation is rather simplistic, assuming a constant elasticity value of responses, but is one approach that minimizes data requirements and facilitates sensitivity analysis with respect to uncertain elasticity parameters.

Empirical implementation of the model is challenging due to the lack of data specific to sheep-producing households in the Yucatán. However, Magaña-Lemus et al. (2013) have previously shown the linkage between income and food security outcomes measured by experienced- based food insecurity scales for different socio-economic groups in Mexico at the national level, and Torres (2015) provided a detailed set of expenditure elasticities for a set of nine food categories that can be used to assess

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[19] Because production by *tras patio* sheep producers is low-input and tends to rely on shared grazing resources and limited time inputs, it may well be possible to increase production with limited impact on income from other sources.

changes in food expenditures in response to income changes[20]. As is likely to the case with many other agricultural systems models not developed with these specific food security indicators in mind, the empirical evidence base is illustrative and suggestive of potential sources rather than empirically specific to this particular setting. We could not find empirical evidence linking dietary diversity to income for Mexico, so the assumed value has a limited empirical basis. For the purposes of illustration, values for expenditure elasticities (Table 9) were selected for the lowest income decile (which tend to have higher numerical values), and the food insecurity elasticity value was approximated based on the values for households below and above poverty lines for income or assets from Magaña-Lemus et al. (2013). The negative value of the FIES means that the degree of food insecurity would decrease as income increases (which constitutes an improvement), and the positive values for the other elasticities indicate increased dietary diversity or consumption expenditures with higher incomes.

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[20] It is relevant to note that the empirical values for both of these studies are based on analysis of household-level data rather than regionally-aggregated data, and thus may require further adaption for regional modeling analyses.

Table 9. Food Security Indicator Elasticity Values with Respect to Income Assumed in the MSSM for Illustrative Purposes

FSI Elasticity	Value
FIES	-0.5
HDDS	0.4
Expenditures on:	
Cereals	0.724
Meats	1.258
Fish	1.664
Dairy	0.897
Oils	1.019
Vegetables	0.914
Sugar	1.239
Beverages	0.682

Sources: FIES estimated based on information from Magaña-Lemus et al. (2013). HDDS is stylized estimate. Expenditure elasticities are from Torres (2015) for the lowest income decile.

The simulations indicate that although growth in demand for sheep meat can increase income for *tras patio* sheep producers in Yucatán, income increases may not be maintained when demand growth slows (Figure 10). When demand growth slows and commercial producers receive subsidies, initial income increases can be more than offset in the long-run—when the supply response for commercial producers reaches its fullest impact. The initial increase in income in the Demand Growth scenario is due to higher prices and increased sales, from which sheep producers throughout Mexico initially benefit. The dynamic supply response over time (after about three years, when demand is assumed to cease to grow) results in lower prices and incomes after the initial increase. In the scenario with subsidies, *tras patio* sheep producers initially see very rapid increases in income because the cost subsidies provide incentives for rapid expansion by commercial producers, who retain additional animals as breeding stock. The number of marketed animals from commercial operations falls and price increases (This is consistent with supply response analyses such as those by Meadows (1970) and

Sterman (2000).) Once this initial supply response has occurred, incomes begin to fall for *tras patio* producers as additional sheep meat supply comes online. As a result, from year 5 to year 9, total income for *tras patio* sheep producers in Yucatán is lower than in the base case, even with demand growth.

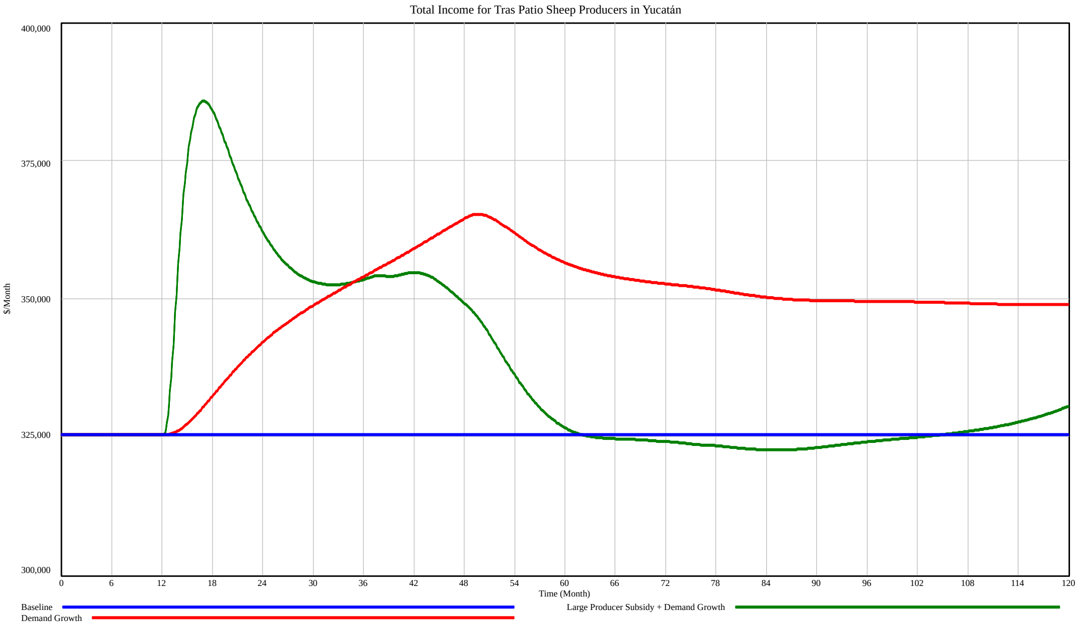

Figure 10. Total Income for Yucatán *Tras Patio* Sheep Producers for Reference (Equilibrium; blue), Demand Growth (red) and Demand Growth with Cost Subsidies to Commercial Producers (green) for 10-year Time Horizon

The impacts on food security indicators mirror the impacts on income in this case (Figures 11 to 13, which is not surprising given the elasticity-based formulation linking these outcomes in the model). This analysis highlights the stability dimension that tends to receive insufficient treatment in many agricultural system model analyses. In this case, the "stability" or "robustness" criterion is not met—the system does not respond to the "shock" of cost subsidies with relative stability in food security outcomes for smallholders—although in this case, that would be considered a good thing due to initial improvements in food security outcomes. The "adaptation" criterion is met in the sense that the system adapts over time to the shock to return to levels of food security similar to those prior to the shock. In this case, "adaptation" is associated with a decline from previous improvements. Although the nature of this assessment is rather qualitative, it highlights the need to distinguish between (often, intended) shocks (e.g., interventions) to improve food security (for which "stability" and "adaptability" would be associated with negative outcomes, and (often, unintended) negative shocks for which stability and adaptability would be considered positive outcomes. It also is relevant to note that "dynamic complexity" (where short-run and long-run impacts of an intervention or shock can differ) applies to food security outcomes for *tras patio* sheep producers. Initially, there are improvements in all three indicators due to increased income, but as demand growth slows, some of the gains are now offset. When large producers are subsidized, *tras patio* producers may see very large initial improvements in food security indicators but may be marginally worse off after the subsidy program has been in operation for four years. Sustaining the improvements in food security indicators can be challenging, even when there are no unexpected shocks.

Given that the simplified representation employed in this stylized analysis implies that changes food security indicators are scaled values of income changes, it is reasonable to question the additional value that is provided by their calculation, particularly given that many agricultural systems model formulations already represent income, which could thus be used as a proxy for food security. First, the different indicators will generally scale differently, so even if their direction of change in this formulation mirrors income changes, the specific numerical values will differ for the food security indicators. This may provide additional relevant insights, particularly when some indicators are deemed of greater importance. Second, this analysis examines proportional changes in regional average values, but this could be complemented with information showing initial starting values and comparing changes over time to relevant thresholds. For example, starting values of per capita grain consumption could be used with proportional change values from the simulation to determine regional average per capita grain consumption among this population to provide another indicator of access, particularly relative to a desired benchmark. Third, the average values here may be useful to suggest how distributional outcomes across the population would change for the food security indicators given increases in average values, for example, the proportion of *tras patio* sheep producers above a threshold value. Although it may be preferable to consider model formulations that represent individual decision makers explicitly (as in agent-based models), useful insights may still be gained from aggregated models such as this if empirical links can be made between regional average outcomes and the distribution of outcomes. Finally, when more than one driver of food security outcomes can be documented empirically and is represented in an agricultural systems model, the scaling between drivers and food security outcomes will not be as direct as it is in this case, even if a similar elasticity-based formulation is used. It is worth noting also that different values of the elasticities would affect the results, with larger values indicating a more pronounced response for both increases and decreases in food security. More sophisticated regional models might also include food security effects on labor productivity and allocation (CLASSES modifies both availability of household labor for agricultural activities as well as its allocation, but not productivity), and the number of producers participating in an activity. These might be best formulated as more disaggregated agent-based models that allow for regional market interactions.

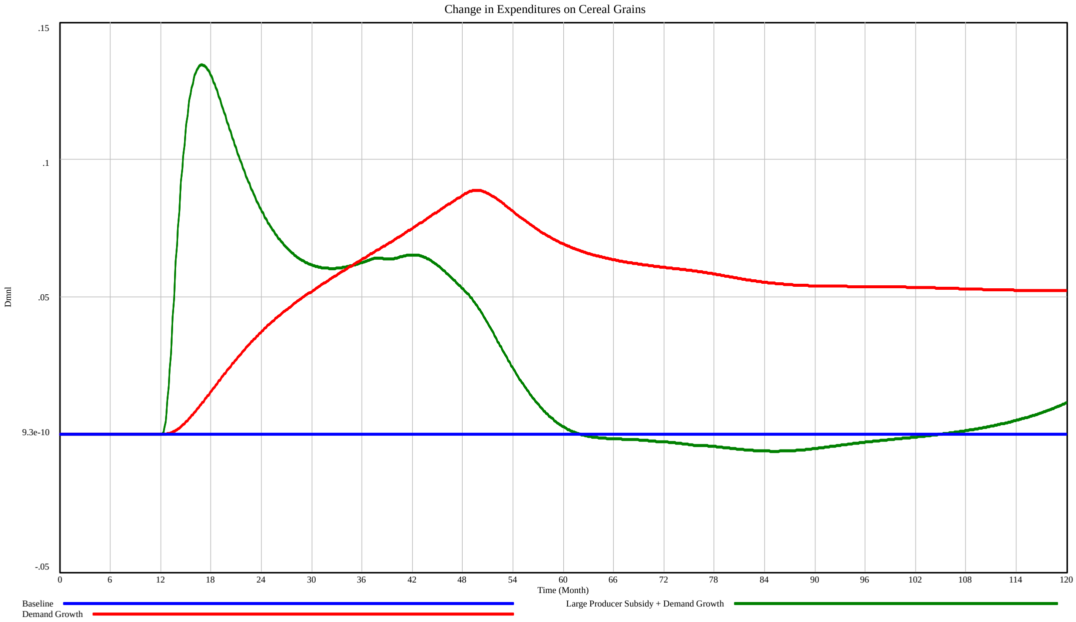

Figure 11. Proportional Change in Expenditures on Cereal Grains for Yucatán *Tras Patio* Sheep Producers for Reference (Equilibrium; blue), Demand Growth (red) and Demand Growth with Cost Subsidies to Commercial Producers (green) for 10-year Time Horizon

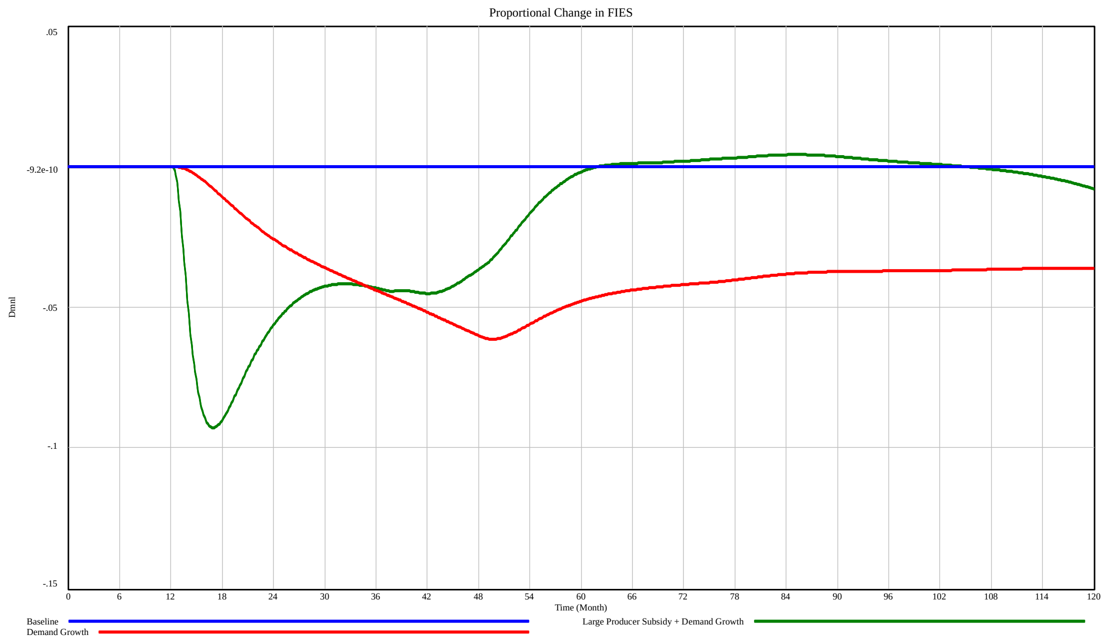

Figure 12. Proportional Change in FIES Scale Value for Yucatán *Tras Patio* Sheep Producers for Reference (Equilibrium; blue), Demand Growth (red) and Demand Growth with Cost Subsidies to Commercial Producers (green) for 10-year Time Horizon

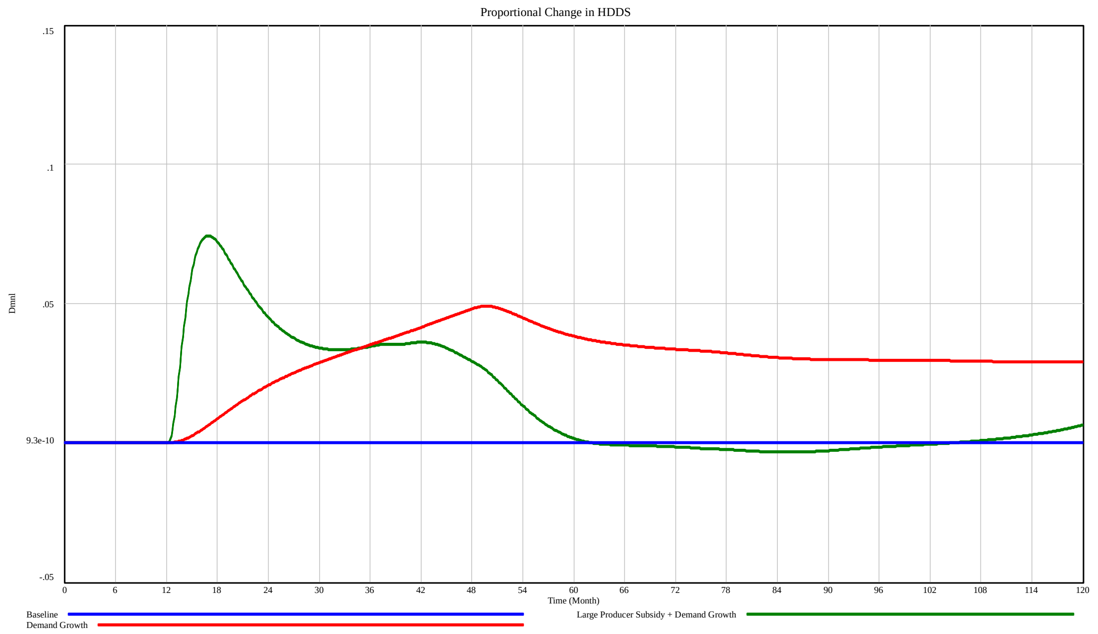

Figure 13. Proportional Change in HDDS Scale Value for Yucatán *Tras Patio* Sheep Producers for Reference (Equilibrium; blue), Demand Growth (red) and Demand Growth with Cost Subsidies to Commercial Producers (green) for 10-year Time Horizon

Similar to the analyses performed with the CLASSES model, we calculated hardness and elasticity values for two indicators and one type of disturbance. The disturbance in this case was a variation in the size of the variable-cost subsidies to commercial producers from values between 10% and 50% (compared to a reference value of 30%). We tested for the sensitivity of FIES and income to variations in these subsidies, assuming a 1.5% annual growth in demand from the beginning of year 2 (month 24) to the end of year 4 (month 48).

The proportional change in FIES deviates significantly (at the 5% confidence bound) from the reference behavior at very small disturbances (Figure 14). (The values in the figure are positive because an increase in the subsidy increases the average value of FIES—a deterioration in food security status.) A hardness or elasticity value indicates the percentage deviation of the variable cost subsidy to the reference value of 30%. A high hardness value therefore implies that when cost subsidies deviate by a small amount from the reference value, they still have a substantive effect on FIES. Whereas these high hardness values indicate high susceptibility to disturbances, both indicators rebound from large disturbances (fairly low values of the elasticity metrics). With the parameter ranges we used for the Monte Carlo simulations, both parameters were able to recover from the maximum disturbance of a 50% cost subsidy. Therefore, and similar to the CLASSES case, while the system seems to be very susceptible to disturbances, it shows at the same time a fairly high degree of adaptability.

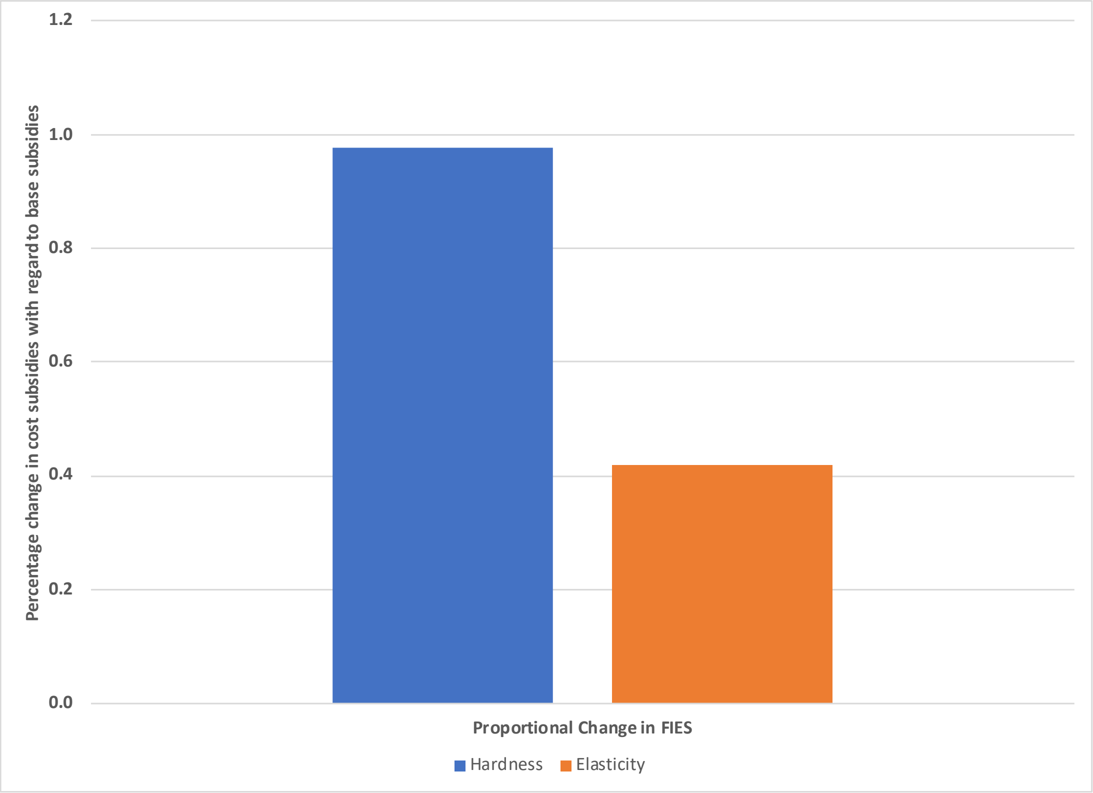

Figure 14. Resilience Analysis for FIES with Variations in Variable Cost Subsidies to Commercial Sheep Producers

8. Overall recommendations: the way forward for improved integration of food security indicators into agricultural systems models

Our review of the current state of practice for the integration of food security indicators in agricultural systems models has considered both conceptual and empirical representations, described the broader set of food security indicators, discussed the (rather limited) empirical evidence linking our recommended food security indicators to the determinants commonly represented in agricultural systems models and illustrated the challenges and benefits of integrating food access indicators into household and regional simulation models. On the basis of these activities we identify the following as key conclusions:

In general, representations of food security in agricultural systems models are not consistent with those viewed as more appropriate by human nutritionists and thus can be improved. To the extent that current agricultural systems models represent food security indicators more closely aligned with those we describe in Section 5, they tend to focus on the availability dimension rather than the access and stability dimensions. Although this often would require additional empirical evidence, indicators of food access (experienced-based food insecurity scales and dietary diversity scales) can and often should be incorporated into analyses of food security outcomes. In addition, greater attention should be paid to the stability dimension—generally requiring a dynamic model with suitable time units and time horizon—with more formalized treatment of the concepts of "robustness" and "adaptability" as in Herrera (2017).

The limited availability of empirical evidence linking indicators of food access to determinants commonly represented in agricultural systems model is a key challenge, but mechanisms exist to address this challenge. We have noted in our review of the modeling literature and in our proof-of-concept analyses that although there is a long history in the economics literature of the determinants of food consumption expenditures, only general evidence about the determinants of two of the food access indicators (FIES and HDDS) is available and from a small number of cross-sectional studies. Although in some cases—say for stylized analyses such as those we undertook—these can be useful, in general an evidence base about the determinants more specific to the particular setting for the simulation model will be appropriate. We have noted before that frameworks such as RHoMIS can provide a good starting point for assessment of food access indicators, but recommend that 1) the determinants be carefully linked to concepts (i.e., determinants) represented in the simulation model, 2) food access be collected based on a panel data (longitudinal) design to allow better representation of the stability component, and 3) analytical methods relating the determinants to the relationships in the simulation model be carefully considered. As an example related to the last point, the CLASSES model assumes discrete impacts of determinants (such as household size or employment status) on the categorial variables FIES and HDDS, which suggests the need for a limited-dependent variable model such as an ordered logit model. For the regional analysis using the MSSM model, the formulation was a simpler one using elasticity values that related changes in income from a Baseline to counterfactual scenarios, which may be estimated with simpler regression techniques or proportional relationships.

Representation of Intra-household (individual) food security outcomes is limited in the agricultural systems modeling literature and should be more fully evaluated in terms of the costs and benefits. Many conceptual models of food security take the household as the unit of analysis, particularly when the focus is on food access (rather than food availability, which is often assessed at a more aggregated scale). Our emphasis on household models is thus consistent with the focus on food access and agricultural systems models, but we note that the utilization component of food security uses individuals rather than households as the units of observation. We believe that additional work to assess the feasibility, costs and benefits of incorporating food access indicators for individuals (e.g., already illustrated by the use of the HDDS specific to women in a few published papers) is relevant.

Extensions to include representation of "food and nutrition security" outcomes should be further evaluated. We have justified our focus on the access and stability dimensions of food security by describing the need to move beyond availability-only measures and the challenges of modeling the utilization elements that are generally the focus on FNS. However, we recognize that for some purposes the linkages between agricultural systems and utilization indicators (especially maternal and child nutritional status) may be of great interest and importance. This is true in part because in some sense they are these 'ultimate' indicators that supply evidence about whether the larger set of the pathways is functioning adequately. As is the case for modeling our three recommended food security indicators, a challenge is the availability of empirical evidence linking determinants to utilization outcomes. The determinants of utilization tend to transcend those typically included in agricultural systems models, encompassing such factors as care-giving behavior, water quality, exposure to disease and toxins, access to health care, and numerous others. However, Randolph et al. (2007) illustrated in a conceptual model that some of the elements determining nutritional outcomes (as contrasted with food security outcomes) can depend on the interactions of the agricultural system itself, as measured by land and labor allocation, income, exposure to zoonotic disease from livestock owned, water quality and consumption patterns. The framework by Kadiyala et al (2014) illustrates similar concepts in a more generally applicable framework. Although these could still be empirically challenging to implement, there is a reasonably lengthy history of empirical analyses of the determinants of nutritional outcomes (not reviewed herein) that could facilitate integration into agricultural systems models. Representing those factors more directly related to agricultural system outcomes (assuming other not included are constant) could be a starting point for analyses linking agricultural systems models and FNS.

Next steps

Given the foregoing, we encourage a number of follow-on steps, including:

- Broad dissemination of the findings of this study to the agricultural systems modeling community (e.g., through an *Agricultural Systems* article) to raise awareness of the current limitations of modeling practice with respect to food security outcomes, to encourage more accurate representations of how current modeling approaches do (or do not) align with a recommended focus on access and stability, and collaborations to develop the empirical evidence base needed for inclusion of food access indicators other than food consumption expenditures;
- Dissemination of the findings of this study to the nutrition community through conference presentations, a journal article and personal communications with nutritionist colleagues working in the agriculture-nutrition space in particular. The goal is to raise awareness of agricultural systems modeling approaches, what they entail, and their potential for expanding the boundaries of inquiry regarding the impacts of food systems and agriculture on nutrition outcomes.
- Development of a broader base of empirical evidence about the determinants of the two less-well-studied food access indicators and their linkages to variables included in agricultural systems models;
- Development of efforts to extend existing agricultural systems models to include improved representations of food access indicators, to further assess the challenges and benefits of these efforts. This will likely require additional data collection to document the linkages between food access and agricultural systems model

variables (as noted above), which may be facilitated by the use of frameworks such as RHoMIS (Hammond et al. 2017);

- Further assessment of the costs and benefits of more specific representation of intra-household food security outcomes in agricultural systems models—for which there is currently limited evidence;
- Further assessment of the costs and benefits of representing utilization indicators (such as nutritional status) in agricultural systems models. This may require broadening the boundaries of existing models (increasing their complexity) to account for the interactions with other factors such as health status but these indicators will often be of interest for the purposes of programmatic or policy assessment. Despite increased complexity, modeling nutritional outcomes may be facilitated by the larger empirical evidence base (e.g., Smith and Haddad, 2015) about the determinants of nutritional outcomes.

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