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# Food security outcomes in agricultural systems models: Current status and recommended improvements

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## ABSTRACT

Improvement of food security is a common objective for many agricultural systems analyses, but how food security has been conceptualized and evaluated within agricultural systems has not been systematically evaluated. We reviewed the literature on agricultural systems analyses of food security at the household- and regional-levels, finding that the primary focus is on only one dimension of food security—agricultural output as a proxy for food availability. Given that food security comprises availability, access, utilization and stability dimensions, improved practice would involve more effort to incorporate food access and stability indicators into agricultural systems models. The empirical evidence base for including food access indicators and their determinants within agricultural systems models requires further development through appropriate short and long-term investments in data collection and analysis. Assessment of the stability dimension of food security (through time) is also particularly under-represented in previous work and requires the development and application of appropriate dynamic models of agricultural systems that include food security indicators, coupled with more formalized treatment of robustness and adaptability at both the regional and household levels. We find that agricultural systems models often conflate analysis of food security covariates that have the potential to improve food security (like agricultural yields) with an assessment of food security itself. Agricultural systems modelers should exercise greater caution in referring to analyses of agricultural output and food availability as representing food security more generally.

## 1. Introduction and motivation

The linkages between agriculture, nutrition and food security have long been recognized in various conceptual frameworks. Initiatives 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 and food security 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 and nutrition security the

linkages between these outcomes and the performance of agricultural systems can be vitally important. Agriculture's linkages to food security are crucial for many farm households in low- and middle-income countries, particularly those facing soil degradation, decreasing water availability and increasing climatic variation (FAO, 2018).

Despite the recognition of these important linkages and challenges, there is a limited number of studies that include explicit quantitative analysis of the linkages between food security and agricultural systems. In a review of previous research Stephens et al. (2018) noted the gap between conceptualization and quantitative implementation of linkages between agricultural systems and food security, stating:

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*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 assessment of value chains, food preferences, and 'food environments'.

A few studies (e.g., Laborte et al., 2007; Laborte et al., 2009; Stephens et al., 2012; Kopainsky and Nicholson, 2015; Marín-González et al., 2018) have tried to link agricultural systems models with food security outcomes to understand evolving intertemporal dynamics and assess the impacts of agricultural system intensification. However, such studies are few and employ limited number of indicators of food security (e.g., proportion of household caloric needs met) with a focus only on household-level outcomes.

Thus, there is a crucial need for and large potential benefits to linking agricultural systems analysis and food security outcomes with greater breadth, frequency and consistency. The benefits would include better ability to evaluate the interlinked impacts of interventions designed to improve food security, human welfare or agricultural outcomes. We contribute to building this knowledge base by assessing the current status of incorporating food security concepts and metrics into agricultural systems models, particularly those developed for low-to-middle-income-country settings with significant populations engaged in agricultural production. We begin with a review of the quantitative indicators used to assess four different dimensions of food security and their multi-scale and semi-hierarchical attributes. We then review literature on modeling analyses of food security at the household and regional levels to assess the use frequency of different food security indicators. On the basis of this review, we recommend and justify the incorporation into agricultural systems analyses of three metrics focused on food access as well as methods to assess the stability dimension of food security. These metrics and the stability assessment can be included in agricultural systems analyses and will begin to address the current gaps in understanding of the complex relationships between agricultural system and food security outcomes. We conclude with a discussion of the challenges of implementing the recommendations given the state of current agricultural systems models and data availability.

## 2. Review of food security concepts and indicators

Jones et al. (2013) describes four commonly-recognized dimensions of food security, namely 1) food availability; 2) food access; 3) food utilization; and 4) stability over time (Fig. 1). More specifically, these dimensions have been identified and documented as distinct but inter-related aspects of food security status at levels from individuals to nations. Further, food security cannot be fully assessed without consideration of each of these dimensions (Upton et al., 2016).

*Food availability* was among the first food security metrics used from the 1950s to the 1970s, and has focused on food balance tables or aggregate commodity production (Upton et al., 2016; Jones et al., 2013). Availability is most often measured at a national or regional scale, consistent with its initial purpose to assess whether increases in food production would be sufficient for growing populations and concerns about the negative impacts of supply shocks on food prices. In agricultural systems modeling, availability is most frequently represented at the national level by supply (production plus net imports) at the farm or household levels by production or yields per unit land.

*Food access* metrics date from the 1980s, following Sen's (1981) work on how entitlements influence food security. Food access goes beyond food availability to consider acquisition patterns and processes that govern distribution of available food, which focuses greater attention on inequities and constraints to food entitlements. Food access is most often assessed at the level of the household or individual (Jones et al., 2013). Food access has multiple dimensions (Fig. 1) and thus many potential metrics (Appendix Table 1). The more recent literature from the nutrition field has focused on the development and application of experienced-based indicators of food access, which rely on an individual's subjective assessment of her or his household's recent ability to access food. These experienced-based metrics represent key aspects of food *access and acquisition*, as well as temporal consumption patterns and important quality metrics of acquired food, like dietary diversity. Specific indicators include the Food Insecurity Experience Scale (FIES) or Household Food Insecurity Access Scale (HFIAS), both of which use a series of yes/no questions to assess the food security experience of an individual or household. The Household Dietary Diversity Scale (HDDS) measures the 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 h. Additional detail on these metrics and others is in Appendix Table 1.

*Food utilization* has received more attention since the 1990s and focuses on food allocated, food consumed and resultant nutritional status for individuals. Indicators of *utilization* summarize and synthesize data on intra-household allocation of a household's acquired food, the nutritional and overall quality of this food and the capacity of different household members to metabolize the nutrient-content of acquired food, which may vary across individuals due to their health status or the status of complimentary systems, like access to water and other health systems (Jones et al., 2013). Examples include anthropometry scores, particularly for children, such as the height-for-weight score, or mid upper-arm circumference measurements, as compared to a reference population for a given age and gender. Standard weight and mid upper-arm circumference measurements are rapid to administer and require relatively less training as compared to recumbent length or standing height measures used to assess child stunting. These anthropometric data along with age
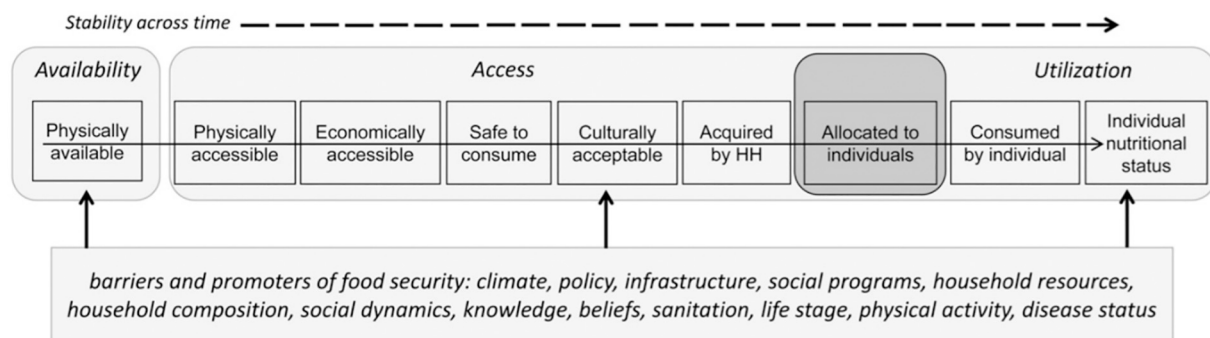


**Fig. 1.** Dimensions of food security and causal factors relevant for consideration of linkages with agricultural systems analyses (Jones et al., 2013).

information are commonly collected as part of large-scale surveys to develop anthropometric indices that can be used for assessing the utilization component of food security.

*Stability* is an additional dimension of food security, but is qualitatively different because it addresses the intertemporal behavior of the other three dimensions. The stability dimension of food security refers to the stability over time of the availability, access and utilization dimensions at all times including the impact of extreme weather events, energy scarcity, and economic or social disruption (Pangaribowo et al., 2013). Metrics employed to assess stability are diverse, but have included those at the Individual level (e.g., number of days unable to work), the household level (e.g., number of days of household food stocks) and national levels (e.g., index of variability of food production). More recent literature (e.g., Upton et al., 2020; Cissé and Barrett, 2018; Béné et al., 2016; Upton et al., 2016) has noted the conceptual overlap of the stability component of food security and resilience concepts from socio-ecological analyses, including the specification of stability metrics that encompass availability, access and utilization.

The nature of these indicators suggests challenges in the conceptual framing of analyses of food security and implementation of empirical analyses. First, the indicators frequently have been applied at different levels of aggregation (scales) ranging from national aggregates for food availability to individual status for food utilization (Jones et al., 2013). Second, multiple scales indicate differences in the causal processes that would be appropriate to consider in a modeling framework. For example, modeling national-average crop yields would employ different methods than modeling yields at plot level. In principle, differences of scale can be addressed in agricultural systems analyses (for example, by modeling only household-level outcomes), but this creates a conceptual gap between the typical usage by human nutritionists and the practice of the agricultural systems modeling community. Finally, these indicators are to some degree hierarchical. Food availability is a prerequisite for food access, and food access is a prerequisite for food allocation utilization. Stability requires that each of availability, access and utilization is adequate over time, even in the face of shocks.

## 3. Representation of food security outcomes in agricultural systems models

To assess how food security is currently being represented in agricultural systems models, we reviewed literature that focused on the household and regional food security assessments, and then concentrated on the subset of this literature that incorporated consideration of agricultural production. To do this, we first conducted Scopus searches for the terms "Household Food Security Model" and "Regional Food Security Model", to identify the extent of existing research on food security modeling at scales most important for agricultural systems modeling. We acknowledge that many possible alternative search terms might have been used, but these were selected because they were hypothesized to yield most of the relevant literature with less of the broader literature on food security not directly relevant for our purposes. The initial Scopus search returned 993 references that analyze food security at the household level and 643 references at the regional level. An initial review indicated that this literature is concentrated in three main categories: 1) analysis of high-income settings, without explicit consideration of agricultural production; 2) analysis of low- and middle-income settings without explicit consideration of agricultural production and 3) analysis of low- and middle-income settings with explicit reference to agriculture. This last category is the focal point for our analysis, given the more direct potential linkages with agricultural systems models.

Our intention was to focus on food security indicators in household- and regional-level 'agricultural systems models', defined as an empirical model that includes biophysical content, sometimes complemented by economic content. This frequently implies a simulation model 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] Household models focus on outcomes at the level of an individual household, and we define "regional" as a higher level of aggregation than an individual household, which can encompass various spatial aggregations (e.g., at the level of a country or its subregions).

We reviewed the abstract for each of the 993 search results for household models to assess whether each was likely to be consistent with our purpose. The majority of papers utilized statistical methods with cross-sectional data to assess various causal relationships between food security and one or more agricultural variables of interest. When the use of this approach was obvious based on the abstract, those papers were elimintated from futher consideration as not consistent with our purpose. This process yielded 88 household-level papers–to which three additional papers were added based on reviewer recommendations—that wereassessed in greater detail (listed in Appendix 3). A similar process applied to the 643 search results for regional models yield 26 papers assessed in greater detail (listed in Appendix 4).

Our focus on agricultural systems models and food security limits the literature relevant for our purpose. Although there is large and continuously-growing empirical literature on the linkages between agriculture and various indicators of food security, we focus our review on analyses that have been formalized in empirical simulation models. The broader literature of analyses linking agriculture to food security outcomes such as found in the 993 household and 643 regional search results can be a valuable complement to the development of improved agricultural systems models, but we deemed a comprehensive review of this larger literature as outside our scope.

### 3.1. Food security representations in household-level models

The abstract for each of the 91 household-level papers discussed both food security and agriculture in a way that appeared consistent with an 'agricultural systems model' as defined for our purpose. Closer examination of the papers' contents indicated that not all of the analyses aligned with our intended focus.More than half of the household studies (59) used statistical methods to assess associations between variables and not biophysical simulation. We completed a review of the food security metrics for all 91 papers and determined that a summary including all of them would provide insights relevant to an assessment of food security in agricultural models. Inclusion of all studies highlights the contrast between the types of metrics used in agricultural systems models and those used in other types of analyses (discussed further below). Broader inclusion also emphasizes the challenges of implementing recommendations for representing food security in agricultural systems models and the need for complementary statistical analyses. The practical implication of including only some statistical studies identified by the search terms is that our summary table will show a lower proportion of these studies, but this should not affect the main conclusions of our assessment with regard representing food security metrics in agricultural systems models.

We assigned each of the 91 papers to one of four categories. The first category is *Analyses that are food security motivated, but food security itself is not modeled* (11 papers).[2] Food security is invoked in the paper motivation or in the abstract, but food security is implicitly equated to yields or increased production without consideration of other indicators. The second category comprises papers for which *One or more metrics representing a component of food security are analyzed as a function of a*

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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.

[2] These classifications (1,2,3,4) are shown in the Appendix Table 3, in the column marked 'Agricultural Systems Model and Type of Analysis' (1–4) (the fourth column of the table).

*limited number of agricultural system level variables (40 papers).* This literature most often assesses statistical relationships between different agricultural household production variables and food security status is assessed with a validated indicator. A third category is *Analyses with an agricultural system model and prediction of some indicator of food security status (25 papers).* These papers often employ a 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. Agricultural system outputs, typically yields, but also potentially production of specific food characteristics, like macro- and micronutrients contained within food output, are used to make inferences about food security metrics. *More integrated biophysical or agricultural system modeling at the household level that considers both agricultural and food security outcomes (15 papers)* constitutes the fourth category. These studies utilize biophysical or agricultural system models (either household or regional level) combined with a household decision-making model to examine interactions between the biophysical system and food consumption patterns, choices, vulnerabilities and security. The papers in the fourth category represent the most integrated presentations of the interactions between agricultural systems and food security outcomes, but they are relatively few in number. These papers also frequently simplify human decision making to a great degree, leading to a limited knowledge base on the full range of human decision-making processes and 'psychometric' food security indicators in use in the food security and nutrition research communities and their interactions and influence within agricultural systems models.

We then documented the use of food security indicators in each of the household analyses, assigning each to the categories of availability, access, utilization, stability and other (Table 1). Of the models using other than statistical methods, measures of availability, especially yields or production (in quantity or calories) dominated, with little consideration of access indicators and only one assessment of the utilization dimension (via inclusion of anthopometry scores in Ogot et al., 2017). Indicators other than those readily categorized into availability, access or utilization (e.g., crop prices or other index values) occurred nine times. Among papers that used methods other than statistics there were only five assessments of *food access*, and four were food consumption amounts or expenditures. Access indicators were more frequently used in statistical models than availability indictors. All uses of experienced-based food insecurity or dietary diversity indicators were from statistical models, which indicates essentially no use of these indicators of food access in agricultural systems models.

In principle, assessment of the stability component requires a dynamic (multiple-time-period) model to represent both a relevant *time horizon* (e.g., the length of time necessary to assess stability) and a relevant *time unit of observation.*[3] By this definition, 18 of the 88 papers represented a sufficient time horizon (ranging from 1 to 100 years) and unit of observation (yearly, monthly, quarterly, or by growing season) that could allow assessment of the stability component. None of the papers included a formal analysis of stability metrics, but four papers (Tittonell et al., 2009; Stephens et al., 2012; Lázár et al., 2015; Rigolot et al., 2017) reported availability or consumption values relative to a consumption threshold.

Very few of these publications explicitly addressed the issue of food security from an intra-household perspective, that is, at the level of an individual. Only three studies mentioned or employed individual-specific metrics, and none of these used a simulation modeling approach. Islam et al. (2018) used a HDDS indicator specific to women

as a dependent variable in a statistical analysis of the impacts of farm diversification. The RHoMIS framework (Hammond et al., 2018) 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.

In addition to summarizing the use of general types of indicators and analytical methods, we reviewed more specifically the nature of calculations used for food security indicators. The types of calculations used for household studies are diverse, which makes a concise summary challenging. Statistical analyses using household survey and other secondary data often assessed one or more indicators of availability or access as functions of household head, farm, and locational characteristics. Optimization models most frequently included constraints to ensure some minimum value of food availability (e.g., Amede and Delve, 2008). Simulation models used either simple regression models (e.g., Bharwani et al., 2005; Beyene and Engida, 2016) or more detailed biophysical models (e.g., Lázár et al., 2015) to predict yields or production as a measure of food availability. Some models (e.g., Holden and Shiferaw, 2004; Louhichi and Gomez y Paloma, 2014) also include more sophisticated demand models to represent food consumption expenditures. A detailed summary of the types of calculations for each of the 91 studies is provided in the supplemental materials.

### 3.1.1. Food security representations in regional-level models

The 26 papers are a diverse group of analyses, using a variety of methods applied in different settings. Four studies used primarily statistical methods but were retained for the assessment. As for the review of household models, we documented the food security indicators used in each of the regional models, assigning each to the categories of availability, access, utilization, stability and other (Table 2). Of the indicators reported, 22 were variables 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, yield was reported seven times. National or regional level production was more commonly used than household or per capita production, and indicators of caloric availability were reported three times.

Food access indicators were reported less frequently than food availability indicators, with 12 variables reported. Three of these instances used experienced-based food security scales similar to the Food Insecurity Experience Scale (FIES) or Household Food Insecurity Access Scale (HFIAS) but only one (Cordero-Ahiman et al., 2017) used an experience-based instrument recommended as best practice (the Latin American and Caribbean Food Security Scale, or ELSCA). The indicators were a form of consumption measure, such as aggregated food consumption, food consumption per capita and calories per capita. 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. Two studies employed measures that primarily focus on utilization; two reported caloric intake and one used a proportion of children underweight. 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 (noted as "other" in the footnote to Table 2).

The integration of these food security measures into alternative modeling approaches is also of interest (Table 2). Models using consumption or caloric intake[4] more frequently employed models with an economic focus such as partial equilibrium or simulation models, or integrated simulation models. A number of types of models used yields or production as key indicators, but especially those that were classified

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[3] 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.

[4] 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.

**Table 1**
Frequency of food security outcome indicators and model types for $N = 91$ papers listing "Household Food Security Model" in search terms and meeting selection criteria.

| Food Security Indicator Category and Specific Indicator | Model Type and Frequency of Indicator Use | | | | | |
|---|---|---|---|---|---|---|
| | Partial Equilibrium, Optimization, CGE | Simulation, Biophysical | Simulation, Integrated | Statistical | Other | Total |
| **Availability** | **19** | **12** | **8** | **23** | **5** | **70** |
| Caloric availability or intake | 6 | 4 | 4 | 14 | 3 | 31 |
| Yields or production | 15 | 8 | 4 | 9 | 3 | 39 |
| **Access** | **2** | **0** | **3** | **31** | **2** | **38** |
| Consumption[a] | 2 | | 2 | 12 | 1 | 17 |
| Food insecurity scale | | | | 11 | 1 | 12 |
| Dietary diversity | | | 1 | 8 | | 9 |
| **Utilization** | **0** | **0** | **0** | **1** | **0** | **1** |
| **Other**[b] | **2** | **2** | **1** | **4** | **0** | **9** |
| **Total** | **23** | **14** | **12** | **59** | **7** | **118** |

Totals for indicators are larger than the number of papers reviewed because some papers reported multiple indicators. Other types of models considered included conceptual models, economics-only simulation models, and other simulation models, but no papers in the published literature were most appropriately assigned to these categories.

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

[b] Other 'food security' indicators include coping strategy index, nutrient content of food, self-assessment of food scarcity (but not validated scales such as 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.

**Table 2**
Frequency 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 | Partial Equilibrium | Bio-physical Simulation | Economic Simulation | Integrated Simulation | Other Simulation[a] | Statistical | Conceptual | Total |
|---|---|---|---|---|---|---|---|---|
| **Availability** | **3** | **4** | **1** | **5** | **7** | **0** | **2** | **22** |
| National or regional production | 3 | | 1 | | 2 | | 1 | 7 |
| Net imports | | | | | 2 | | | 2 |
| Household production | | | | 1 | | | | 1 |
| Per capita production | | 1 | | | 1 | | | 2 |
| National caloric availability | | | | | 1 | | | 1 |
| Per capita caloric availability | | | | 2 | | | | 2 |
| Crop yields | | 3 | | 2 | 1 | | 1 | 7 |
| **Access** | **4** | **0** | **2** | **1** | **2** | **3** | **0** | **12** |
| Per capita calories consumed | | | 1 | | | | | 1 |
| Experience-based food (in)security scale (e.g., FIES, HFIAS) | | | | | | 3 | | 3 |
| Household calories consumed | | | | 1 | | | | 1 |
| Household food consumption | | | | | 1 | | | 1 |
| Per capita food consumption | 1 | | | | | | | 1 |
| National or regional consumption | 3 | | 1 | | 1 | | | 5 |
| **Utilization** | **0** | **0** | **0** | **0** | **3** | **0** | **0** | **3** |
| Individual food consumption | | | | | 1 | | | 1 |
| Individual caloric intake | | | | | 1 | | | 1 |
| Percent children underweight | | | | | 1 | | | 1 |

Totals do not add to 26 because some manuscripts included more than one indicator. Also, 2 papers were entirely conceptual and one paper had no model but proposed yields as an indicator of food security. Other types of models considered included conceptual models but no papers in the published literature were most appropriately assigned to this category. Other 'food security' indicators not reported above include quite indirect measures of food security: coefficient of variation of grain prices, "food demand = food supply", a household income threshold, an index of supply chain coordination and stylized game theory monetary payoffs.

[a] Other simulation models include those with a supply chain focus, agent-based models with a water focus, models focusing on grain storage, use of others estimates of food availability with statistical linkages to underweight distribution and stylized game theory models.

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 of 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.

Consistent with our assessment of household-level models, analysis of the stability component of food security was limited in regional

models. Two studies reported how the proportion of food-insecure households changed over time (Akter and Basher, 2014; Harttgen et al., 2016).

Seven of the models reviewed would be characterized as dynamic in the sense of simulating outcomes over time although in some cases neither the time horizon or time unit of observation is clearly stated (see Appendix Table 4). Although reporting outcomes over time, these studies did not formally assess stability. Five studies report outcomes for a single future year or multiple future years but without results for the

intervening time periods. Although there is a temporal dimension to these studies, they are less useful for addressing the 'stability' component of food security because of their focus on long-term trends.

The types of calculations used to determine food security outcomes in regional analyses are diverse. Statistical analyses focus on experiential indicators of food access (e.g., Cordero-Ahiman et al., 2017; Djebou et al., 2017) and use limited-dependent variable methods to assess the impact of household and regional characteristics. Simulation studies most often used price-responsive supply curves to predict food production (e.g., Wailes et al., 2015; Dorosh et al., 2016) although some studies used biophysical simulation models (e.g., Mainuddin et al., 2011; Moore et al., 2012). Analyses using integrated market models (e.g., Mason-D'Croz et al., 2016) combine calculations of food availability and food consumption. A few regional studies include more sophisticated food demand models (e.g., Bakker et al., 2018; Wossen et al., 2018) to calculate food consumption as a measure of food access. A complete listing is provided in the supplemental materials.

## 4. Recommendations to improve consideration of food security outcomes in agricultural systems models

Our assessment of household- and regional-level models documents two important limitations with modeling analyses linking agriculture to food security outcomes: 1) over-emphasis on availability indicators (and perhaps implicitly assuming that this leads to unambiguous improvements in the other indicators) and 2) limited treatment of the access, utilization and stability dimensions of food security. This suggests four recommendations to improve representations of food security outcomes in agricultural systems models:

1) Avoid equating "food availablility" with "food security";
2) Incorporate food access indicators;
3) Assess stability outcomes for food security indicators;
4) Develop empirical evidence linking outcomes in agricultural systems models to food access outcomes.

These recommendations identify strategic objectives or directions that would improve agricultural systems modeling analyses of food security, rather than providing a detailed implementation plan encompassing a wide range of settings. This section further discusses these recommendations and the challenges that must be overcome to implement them. Our companion paper (Nicholson et al., 2021) describes the challenges and opportunities of modifying one household and one regional model to align more closely with these recommendations.

### 4.1. Avoid equating food availability with food security

Our analyses indicated that the most common indicator of food security in the studies reviewed (particularly simulation modeling studies) was food availability. Variables for food production (e.g., crop yields) are common in agricultural systems models, which makes them convenient and relevant for assessment of food security. However, the use of these indicators as the only indicators of food security can be misleading when the underlying assumption is that 'more food' equates to improved food security. As noted above, food security is a multi-dimensional concept and in principle all dimensions matter for determining if a population is food secure. The use of availabily as a proxy for the other dimensions is more appropriate when there is a high degree of correlation between availability and other outcomes. A growing body of empirical evidence to the contrary arose during the 1980s for

assessments at an aggregate level (Upton et al., 2016).

Efforts to operationalize food access indicators were motivated in part by the recognition that food availability is necessary but not sufficient for the achievement of food security at national, regional, household or individual levels. Food insecurity can exist for some populations in times and places with adequate aggregate food supply and availability. For example, it has been broadly recognized that national-level food availability is only weakly correlated with indicators of undernutrition, with child underweight rates, varying widely across countries with the same levels of average per capita energy supplies (Haddad and Smith, 1999), which also reflects the challenges of assessing food security outcomes at different levels of aggregation.

Further, most low-income rural farming families depend predominantly on purchased food rather than home-produced food for household consumption (Global Panel on Agriculture and Food Systems for Nutrition, 2016), so even for these households analyzing agricultural yields is not sufficient to account for all food consumed. Finally, many conceptual frameworks (e.g., Kadiyala et al., 2014; Randolph et al., 2007) recognize that complex pathways exist between increased agricultural production and food security outcomes—for example, that increased production may be sold and used for purposes that have little or even negative effects on food security outcomes. 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.

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. This recommendation is easily implemented at a very low cost. If a modeling analysis focuses only on food availibility outcomes such as production or yields, these could be described as "*potential contributions to improved food security*", rather than as more definitive indicators of "food security". Such analyses could also discuss their results as relevant to the *food availability dimension* of food security, but this aligns less well with the higher level of aggregation used by human nutritionists.

### 4.2. Incorporate food access indicators

We recommend that agricultural systems models focus to a much larger extent than previously on incorporating food access indicators. As noted above, the historical development of food security indicators started with availability, added access, and focused more recently on utilization. That may seem to imply that agricultural systems models should now focus on utilization (and a few already do). However, we argue that given the current characteristics of agricultural systems models and the hierarchical relationships among indicators, inclusion of food access indicators is an appropriate goal.

Inclusion of sufficient consideration of the *utilization* dimension of food security in agricultural systems models would be quite challenging. Utilization typically assesses individual nutritional outcomes that result from the amount and quality of food actually consumed by individuals. There are significant challenges to assessing individual-level health and nutritional status without hard-to-obtain clinical health and nutrition indicator data. Considerable difficulty in ascribing a causal relationship between agricultural production indicators and individual-level diet or nutrition outcomes can result. 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 closely related to the nutrition outcomes of interest, and is therefore easier to conceptualize and model as a direct determinant of these outcomes. Ballard et al. (2013) also note growing evidence that "the utility of anthropometric measures as proxy indicators of household food security is questionable" and indicate that experience-based indicators "can be used to complement anthropometric data and potentially identify vulnerable populations before malnutrition becomes manifest."

We recommend that three food access indicators would have high value and greater potential to be incorporated into agricultural systems models at present. These three indicators are 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), and 3) measures of household dietary diversity such as the Household Dietary Diversity Score (HDDS). These metrics are complementary representations of food access, given its multiple dimensions (Fig. 1). Food consumption expenditures link incomes earned through agriculture for farming households with their food consumption choices, and align with conceptual and analytical frameworks for analyzing household decision making, such as the Agricultural Household Model (Singh et al., 1986). FIES and HFIAS are experienced-based metrics represent key aspects of food *access and acquisition,* as well as temporal consumption patterns. HDDS and similar scales assess one important quality metric of acquired food, dietary diversity. As has been recognized (e.g., Upton et al., 2020; Béné et al., 2016; Upton et al., 2016) different metrics can yield different conclusions about the food security status of populations, so the use of multiple metrics for food access is appropriate when feasible. We further explore the different patterns for food access metrics in response to yield or policy shocks in our companion paper.

Two challenges to implementing these indicators in agricultural systems models relate to model structure and empirical relationships. The first of these challenges is that representation of food consumption expenditures requires representation of household-level decision making in agricultural systems models. Of those we reviewed, many models avoid explicit consideration of household-level decision making about food distribution and consumption, or make decisions exogenous or rule based (e.g., per capita estimates). Many agricultural systems models simulate physical quantites of crop or livestock production, which is then assumed to be available for consumption. Production implicitly is equated with consumption and this may be compared to a self-sufficiency benchmark. There is no active decision making in the model about consumption choices by household members. In models with these characteristics (e.g., Rigolot et al., 2017), there is also no feedback from the household decisions and outcomes back to the underlying production model (e.g., desired consumption patterns by the household do not influence production decisions), and only potential consumption can be compared across enterprise systems. Models with these characteristics provide incomplete proxies for food security comparisons across agricultural systems as food acquisition choices are not actively modeled.

A more complete interface between biophysical and farmer decision-making would need to include a) explicit assumptions about which biophysical information (e.g., yields) can be accurately observed by the farmer, and b) structural modeling of the consumption preferences, choices and economic objectives of farm households. Modeling food expenditures as an additional outcome of an agricultural systems model will thus involve use of an overarching decision-making framework about allocation of farm resources, 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. Assumptions would need to be made about whether a household has flexible level of consumption out of home production, based on changes in market prices for food or other goods. A demand system (e.g., Bakker et al., 2018; Wossen et al., 2018) would require a 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 suggesting relationships of this nature would need to be compared with observed data. This would allow better, and more structural, integration of food security concepts based on access, but this is not currently the state of practice for most agricultural systems models and would involve more long term investment in researching the nature of key underlying mechanisms linking agricultural system and food security outcomes.

The second challenge is data for empirical implementation of these metrics in agricultural systems models. Although data to estimate a demand system may not be available for a specific model setting, the types of data required for analysis of food consumption expenditures have been collected for a longer time and are generally more available or proxied than the experiential food insecurity scales and dietary

**Table 3**
Summary of existing empirical evidence for relationships between determinants and household-level food security indicators and their likely role in agricultural systems models.

| Determinant of Food Security | Food Access Indicator | | |
|---|---|---|---|
| | FIES | HFIAS | Dietary Diversity[a] |
| Model Outputs Used as Food Security Determinants[b] | | | |
| Wealth (Assets) | + | | |
| Income | | + | |
| Income source diversity | | + | |
| Food consumption expenditures | | | + |
| Model Components Used as Food Security Determinants[b] | | | |
| Women's decision-making[c] | + | + | + |
| Livestock ownership | | + | |
| Diversity of livestock species owned | | + | |
| Agricultural production diversity | | | + |
| Employment | + | | + |
| Model Inputs Used as Food Security Determinants[b] | | | |
| Education | + | + | + |
| Number of Children | − | | |
| Household Size | − | − | |
| Social capital | + | | |
| Land ownership | | | + |
| Literacy | | | + |
| Proximity to markets | | | + |
| Peri-urban resident | − | | |

Signs are interpreted as whether an increase in the value of the determinant variable improves outcomes measured by the food security indicators, holding other factors constant. For example, an increase in wealth causes a reduction in FIES, which is shown with a '+' to indicate an improvement. An increase in the number of children causes an increase in the degree of FIES, which is shown with a '-'to indicate a deterioration.

[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.

diversity. Thus, we focus our discussion on the challenges associated with these latter two indicators. Data on FIES/HFIAS and HDDS indicators are being more commonly collected now than in the past, but the empirical evidence base is still limited for many settings already represented with agricultural systems models.

A key issue is how to link outcomes common in agricultural systems models, such as production quantities or incomes, with indicators such as FIES, HFIAS and HDDS. Nicholson et al. (2019) reviewed the existing empirical evidence on the determinants of these indicators (Table 3; a summary of this review is provided in the supplemental materials). To relate these determinants more closely to potential use in agricultural systems models, the determinants were classified by whether they are model outputs, model-generated potential determinants of food security, or model inputs (assumptions). The number of studies of determinants is still relatively small and the evidence is primarily from single-equation (reduced-form) statistical relationships. However, the available evidence does suggest some consistent patterns, e.g., that higher incomes are associated with improved food security as measured by FIES or HFIAS and also with improved dietary diversity (HDDS). Higher levels of food consumption are associated with increased dietary diversity. Household characteristics that would most often be agricultural systems model inputs affect each of the indicators. The small number of studies at present implies that only in a few settings is there sufficient evidence for the linkages between determinants and food access indicators to be employed other than in a stylized manner. However, representing these linkages even as stylized outcomes could still represent an important improvement over the bulk of the literature that does not consider these concepts at all. We show how this could be done in our companion paper. In section 4.4, we discuss further the challenges and path forward for development of empirical evidence on detrminants of food access.

### 4.3. Assess stability outcomes for food security indicators

Food security indicators should be evaluated over time to assess more formally the *stability* dimension. Our review indicates that assessment of stability is uncommon. A limited number of studies were dynamic, and even these most commonly reported outcomes over time without reference to thresholds. A more formal assessment of stability requires appropriate dynamic model structures and methods to compute stability metrics.

Assessing stability requires dynamic models that represent outcomes at relevant time intervals for appropriate time horizons. Our review indicates that a subset of extant agricultural systems models is dynamic, so in principle it should be possible to extend their analysis to consideration of food security patterns over time as well. Even for dynamic models, changes may be appropriate to time observational units to facilitate assessment of stability. 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. Agricultural systems models used to assess stability outcomes should be explicit about why the time horizon and time unit of observation are appropriate and consistent with assessment of stability indicators.

Dynamic agricultural systems models that calculate behavior over time of food security indicators can be used to calculate the probability (e.g., Harttgen et al., 2016) or duration (e.g., Akter and Basher, 2014)

for which availability, access or utilization indicators deviate from some reference (threshold) value, given changes to the agricultural system. This requires specification of an appropriate threshold value, for which a reference standard (such as a minimum recommended consumption) typically will be available. Comparison to thresholds provides one low-cost pathway for improvement of stability assessments in dynamic agricultural systems models.

In addition to stability metrics that assess elapsed time above or below a threshold value, recent literature on the stability of food security uses concepts of *resilience* in the assessment of food security for conceptual framing and empirical measurement (Upton et al., 2020; Ansah et al., 2019; Cissé and Barrett, 2018; Béné et al., 2016; Upton et al., 2016). Béné et al. (2016) note that the resilience approach focuses on the use of indicators assess capacities (absorptive, adaptive and transformational) of a food system that will increase its stability. The causal pathways through which these capacities affect food security, are however, rarely considered in empirical analyses (Ansah et al., 2019). Resilience concepts can be particularly useful for analysis of how different types of shocks affect food security outcomes, and most agricultural systems models have structures that allow for this type of assessment. Assessment of resilience may also provide insights about the causal pathways through which capacities affect food security outcomes.

Drawing upon the recent resilience-oriented literature, operationalizing *resilience* can use methods described by Herrera (2017). The conceptual approach in Herrera assesses four dimensions of resilience (hardness, recovery rapidity, robustness and elasticity) and shows how these can be calculated in dynamic systems models. Two of these resilience metrics are more relevant for assessment of food security. *Hardness* assseses the degree to which a system can resist changes to reference behavior outcomes given one or more shocks. Hardness thus aligns conceptually with the absorptive capacity of a system. *Elasticity* assesses whether a system that is disturbed by a shock can recover to levels observed prior to a shock. Elasticity thus aligns conceptually more with adaptive and transformational capacity. Implementation of assessment of hardness and elasticity metrics requires simulation of the impacts of shocks of different magnitudes, specification of what difference from a reference (baseline) setting constitutes a substantive change, but is otherwise computationally straightforward. Thus, this is a low-cost mechanism to improve stability assessments in dynamic agricultural systems models. We discuss implementation of this approach more fully in our companion paper.

### 4.4. Develop empirical evidence linking outcomes in agricultural systems models to food access outcomes

We emphasize the need to include food access indicators in agricultural systems models because of the limitations noted previously for the use of food availability indicators alone—lack of correlation between production and improved nutritional outcomes due to complex pathways and multiple food acquisition modes even for farming households. However, we acknowledge at present the empirical evidence base is currently insufficient to support robust and reliable integration of consumption expenditures, experience-based food insecurity scales and household dietary diversity in many agricultural systems modeling contexts. Although previous studies have examined the determinants of these indicators and found a few consistent relationships (e.g., higher household incomes improve all food security indicators; Table 3) often these are not specific to the geographic settings modeled

by existing agricultural systems models. This suggests that collection and analysis of these data on determinants are needed to allow analysis of food access in more settings.

Long-term investments are needed to document and refine the relationships between common outputs of agricultural systems models and food consumption expenditures, FIES and HDDS. Data collection frameworks such as RHoMIS (Hammond et al., 2018) provide a good starting point for improving knowledge of the current satus and determinants of food security indicators, including food access. However, development of the empirical evidence base to incorporate food access is best implemented such that 1) the determinants be carefully linked to concepts represented in simulation models, 2) longitudinal data are collected 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. Efforts are also required 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 a starting point, as this body of work is explored and expanded and more is learned about underlying structural relationships between agricultural production, incomes and food access.

## 5. Concluding comments

Our review of the integration of food security indicators in agricultural systems models suggests three principal conclusions relevant for improvement from the current state of practice. First, representation of food security often is not consistent with those indicators viewed as more appropriate by human nutritionists. Current analyses focus primarily on the availability dimension rather than on access and stability dimensions, which can be misleading given the complex pathways between production and consumption. Second, to represent food access, a greater focus on food consumption expenditures, experiential food insecurity scales and measures of dietary diversity would be appropriate. Incorporating access outcomes often will require additional empirical evidence, both the measurement of these outcomes but also an exploration of their underlying determinants, i.e., how these outcomes link to other outputs from the agricultural systems model. Third, much

greater attention should be paid to the stability dimension of food security. Treatment of stability is limited in agricultural systems analysis at present and will require application of dynamic models with suitable time units and time horizons. In addition to representing intertemporal dynamics, there is a benefit to drawing upon concepts from the analysis of resilience for both conceptual framing and empirical measurement.

This paper provides a justification and general suggestions for the improvement of food security outcome predictions in agricultural systems models. In a companion paper (Nicholson et al., 2021), we illustrate the challenges and benefits of our recommendations for two case examples that incorporate our recommended food access indicators into existing household- and regional-level agricultural systems models. This provides a template for future practice, highlights the possibilities and improvements to be gained from incorporating food security metrics beyond production, but also indicates the significant gaps in the current empirical knowledge available to fully document these relationships. The companion paper also highlights key information needs (e.g., linkages between food access indicators and their determinants) and priority areas for application of food security analyses with agricultural systems models (such as food security and climate change and transformative changes in food systems).

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

## Appendix A. Household- and individual-level indicators of food insecurity with a focus on access

| Indicator | Description | Comments |
|---|---|---|
| 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). | Annually as part of the Current Population Survey, incorporated into the National Health and Nutrition Examination Survey (NHANES) as well as data collection tools of other research efforts. Only collected in 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. The data to construct this indicator are likely not widely available in the context of nationally representative datasets. |
| Latin American and Caribbean Food Security Scale (ELCSA) | Similar to HFIAS. 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. | 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. |
| 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-month recall) | 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. Perhaps the most relevant for models meant to compare relationships between agricultural systems and food security broadly. |
| 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" | The HHS is also included in early warning or nutrition and food security surveillance systems and can inform humanitarian response. |

(*continued*)

| Indicator | Description | Comments |
|---|---|---|
| | dimension of food access. The scale uses the last 3 items of the HFIAS (occurrence of severe experiences of food shortage). | 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. 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 | See comment above. |
| 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 h: 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 | Proxy measure of a household's food access. It 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. 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 |
| Food Consumption Score (FCS) | The indicator combines data on dietary diversity and food frequency using 7-day recall data. Respondents report on the frequency of household consumption of 8 food groups. 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 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. 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. |
| 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. This indicator and the IYCDDS are the only diet diversity indicators validated for use as proxies of nutrient adequacy of diets |
| 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) |
| 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) |
| 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 |

(*continued*)

| Indicator | Description | Comments |
|---|---|---|
| | | 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) |

Numerous experience-based food security metrics and methods have been developed that go beyond availability into the other critical dimensions of food security (see Appendix 1 Table above). The Household Food Security Scale Module (HFSSM) was developed for use in the United States based on this formative research (US HFSSM, www.ers.usda.gov/media/8271/hh2012.pdf), and subsequently the Household Food Insecurity Access Scale (HFIAS; technical details can be found at fantaproject.org/monitoring-and-evaluation/), Latin American and Caribbean Food Security Scale (ELCSA; Perez-Escamilla et al., 2007), the Food Insecurity Experience Scale (FIES; Cafiero et al., 2016), and the Household Hunger Scale (HHS; Deitchler et al., 2010) were developed for assessing food insecurity in a similar fashion (Ballard et al., 2013). 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. Given the combination of information gathered about food sources, quality and acquisition patterns, these indicators are often used to provide insights broadly into the food access dimension of food security, as distinct from availability and supply side considerations that are not necessarily tied to the foods chosen, used and consumed by households and individuals.

Assessing coping strategies is another approach to understanding food insecurity, particularly in the food access domain, via uncovering how households maintain access in the face of shocks. 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 can be further used in part as a proxy for food access, in addition to assessing nutrition and other health issues. 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; https://undatacatalog.org/dataset/food-consumption-score) are household-level diet 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; WHO, 2008) (and related Minimum Dietary Diversity (MDD) indicator), the Women's (WDDS) and Individual Dietary Diversity Score (IDDS; FAO, 2011), and the Minimum Dietary Diversity for Women (MDD—W; FAO, FHI 360, 2016) 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. Useful summaries can also be found at the International Dietary Data Expansion Project (https://inddex.nutrition.tufts.edu/data4diets/indicators).

## Appendix B. Summary of the literature on determinants of household food insecurity and dietary diversity[5]

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 et al., 2006a; 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 et al., 2006b). 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 1242 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

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[5] Adapted from Nicholson et al., 2019, section 6.1.

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 and Naccarato, 2019; Smith et al., 2017b). 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 et al., 2017a; 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 (Mengesha 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; Owolade et 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 and 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 and 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 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 to 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 and 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. 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 and 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.

## Appendix C. Listing and description of 91 household models reviewed

| Reference | Setting | Model Classification | Agricultural Systems Model and Type of Analysis[a] | Key reported indicators | Availabiliy Indicators | Access Indicators | Utilization indicators | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| Adewumi and Animashaun (2013) | Examined the relationship among farming households' technical efficiency, dietary diversity and farm income in Kwara state, Nigeria. | Statistical | No, Type 2 | Technical efficiency, dietary diversity, farm income | None | Dietary diversity | None | Not dynamic |
| Ahmad et al. (2016) | Differences in a food security index by types of climate change adaptation strategies | Statistical | No, Type 2 | Developed own food security index using Principal Components Analysis of important drivers of FS | None | None | None | Not dynamic |
| Akerele and Shittu (2017) | Determinants of dietary diversity and linkages to farm production diversity for rural households in Nigeria | Statistical | No, Type 2 | Two-dimensional indices of food diversity (Berry index) | None | Dietary diversity | None | Not dynamic |
| Akerele et al. (2017) | Determinants of intake and dietary adequacy for rural households in Nigeria | Statistical | No, Type 2 | Nutrient intakes compared to RDA, factors affecting adquate intake, diversity as food group count and Berry index based | None | Consumption, dietary diversity | None | Not dynamic |
| Akinola et al. (2009) | Examined the socioeconomic impacts of the balanced nutrient management systems technologies on household incomes and food security of the adopting farmers in Nigeria. | Statistical | No, Type 2 | Yields, incomes, calorie and protein intake | Yields | Caloric availability or intake | None | Not dynamic |
| Ali and Erenstein (2017) | Propensity score matching (PSM) approach was employed to evaluate the impact of adaptation practices on food security and poverty levels in Pakistan | Statistical | No, Type 1 | Food consumption expenditures compared to "amount of food required to lead a healthy life" | None | Consumption | None | Not dynamic |
| Alwang and Siegel (1999) | Linear programming model of representative smallholder households to investigate sources of relative scarcity of labor and land in Malawi. One of the constraints in the objective function is food security (the food security constraint forces the household to produce at least one-half of its maize and groundnut needs). | Optimization | Yes, Type 1 | Value of own consumption, food purchases, land use, incomes, production | Production | Consumption | None | Not dynamic |
| Amede and Delve (2008) | A multiple goal linear programming model was developed to analyze the different production objectives of cash income and/ or human nutrition, through crop land allocation for Ethiopia. | Optimization | Yes, Type 4 | Land allocation, nutrient availability compared to RDA | Caloric availabilty or intake | None | None | Not dynamic |
| Azeem et al. (2016) | Assesses household vulnerability and food security for rural Pakistan | Statistical | No, Type 2 | Prevavlence of chronic undernourishment and food inadequacy based on dietary energy consumption compared to requirements | None | Caloric availability or intake | None | Not explicitly dynamic, but Includes different probability distibutions for different months. |
| Bacon et al. (2014) | Analysis of factors associated with seasonal hunger among smallholder coffee producers | Statistical | No, Type 2 | Seasonal hunger ('thin months') proxied by Percent of foods consumed in the household that were grown on the farm; Was there a moment in which they could not meet their basic food need | None | Consumption | None | Not explicitly dynamic, but percentage reporting 'thin months' during one year described. |
| Baran et al. (2010) | Analysis of the consequences of different water management scenarios on rice, fish, crab and shrimp production in a province in Vietnam | Statistical | No, Type 3 | Rice, fish, crab and shrimp production, household income "food security" | None | None | None | Models five years but in comparative static form |
| Bashir et al. (2014) | Assesses the determinants of caloric intake for households in rural Pakistan | Statistical | No, Type 2 | Caloric intake estimated from 7-day food recall survey | None | Consumption | None | Not dynamic |

14

| Reference | Setting | Model Classification | Agricultural Systems Model and Type of Analysis[a] | Key reported indicators | Availabiliy Indicators | Access Indicators | Utilization indicators | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| Beghin and Teshome (2017) | Examined the linkages between coffee/cash crops and food security in Ethiopia | Statistical | No, Type 2 | Self-reported food shortages, citing Maxwell et al. 2014, but not clearly defined | None | Food insecurity scale | None | Not dynamic |
| Beyene and Engida (2016). | Examined the determinants of household food security among rural households in the Ada Berga district in central Ethiopia. | Statistical | No, Type 2 | Consumption converted to caloric consumption per adult, compared to minimum subsistence requirement | Caloric availability or intake | Consumption | None | Not dynamic |
| Beyene and Muche (2010) | Examined the linkages between irrigation investment and poverty in Ethiopia | CGE | No, Type 3 | Food crop output per labor force | Production | None | None | Not dynamic |
| Bharwani et al. (2005) | Investigated whether individuals who adapt gradually to annual climate variability are better equipped to respond to longer-term climate variability and change in a sustainable manner for a simplified farming setting in South Africa. | Simulation, Biophysical | Yes, Type 3 | Household income and cropping patterns | Production | None | None | 100 year time horizon, shows gradual declines in income over time. No specific stability metrics reported. |
| Darsono (2017) | Examines the correlates of rice self-sufficiency in Indonesia | Statistical | No, Type 2 | Production of rice compared to national averages | Production | None | None | Not dynamic |
| Dhakal et al. (2010) | The first part of this study identified the effect of current forest policy on livestock production using survey data from 259 households in three Nepal hill districts. The second part used a forestry-agriculture integrated model to examine alternative land use policies that could increase household livestock holdings and income while maintaining the environmental services of the community forest. | Optimization | No, Type 1 | Food production by household type compared to needs, and deficit | Production | None | None | Not dynamic |
| Di Falco et al. (2011) | Examined the driving forces behind farm households' decisions to adapt to climate change, and the impact of adaptation on farm households' food productivity | Statistical | No, Type 3 | Quantity produced per hectare of five crops | Production | None | None | Not dynamic |
| Dil et al. (2017) | Large sample analysis of various coping strategies and food security for Bangladesh | Statistical | No, Type 2 | Determinants of food access | None | Food insecurity scale | None | Not dynamic |
| Djanibekov et al. (2013) | The study area is the Khorezm region and three southern districts of the Autonomous Republic of Karakalpakstan located in the low-lands in Uzbekistan, Central Asia. Modeled a cotton–grain commercial farm with an area of 100 ha. | Optimization | Yes, Type 3 | Land use, employment, farm profits, household incomes, per capita food consumption | Production | Consumption | None | 15 year time horizon with results shown annual for cropping patterns and income, percentage change in consumption per capita. No specific stability metrics reported |
| Djebou et al. (2017) | Compared and examined the relationships among agricultural assets, incomes and food security in rural communities of Ghana, Senegal, and Liberia. | Statistical | No, Type 2 | Experience-based food insecurity scale with five questions that has some overlap with the type of questions in FIES. If 2 were answered positively, household was considered "food insecure". | None | Food insecurity scale | None | Not dynamic |
| Dobbie and Stefano (2017) | Stylized agent-based model of farm households in southern Malawi | Simulation, Integrated | Yes, Type 4 | Proportion of food energy deficit households, mean proportion energy from staple crops, count of foods consumed | Production and yields | Consumption, dietary diversity | None | Model is monthly for one-year time horizon. No specific stability metrics reported |
| Ferdous et al. (2016) | Intervention trial with home gardens in Bangladesh | Other | No, Type 3 | Actual production of crops by seasons, reported consumption and sales, household incomes | Production and yields | Consumption | None | Field trial lasted one year, data reported by season. No specific stability metrics reported. |

| Reference | Setting | Model Classification | Agricultural Systems Model and Type of Analysis[a] | Key reported indicators | Availabiliy Indicators | Access Indicators | Utilization indicators | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| Gangwar et al. (2016) | Examined impacts of extreme weather events on farming systems in India | Simulation, Biophysical | Yes, Type 3 | Yields and household incomes | Production and yields | None | None | Outcomes reported for six years. No specific stability metrics reported. |
| Habyarimana and Nkunzimana (2017) | Assessed impacts of land use consolidation policies on household livelihoods in Rwanda. | Statistical | No, Type 2 | Food consumption score, sources of food acquisition, determants of FCS | None | Dietary diversity | None | Not dynamic |
| Hadush (2017) | Examined the impact of time spent looking for animal feed and water on food production and consumption in Ethiopia | Statistical | No, Type 2 | "Approximate" calorie intake and per capita food expenditure, aggregated value of production across crops | None | Consumption | None | Not dynamic |
| Hammond et al. (2018) | Survey instrument designed to quickly assess impact of climate smart agriculture, food security, suitability, gender equity indicator, poverty transitions | Other | No, Type 4 | Household characteristics, crops grown, foood availability, food insecurity indicators, farm income, GHG emissions | Production and yields, Caloric availability or intake | Food insecurity scale | None | Not dynamic |
| Hartter and Boston (2007) | This paper introduced a conceptual framework to examine how individuals and households fulfill daily caloric needs and analyzed the aggregate effects on resource availability and consumption in the hill country of Nepal. | Simulation, Integrated | Yes, Type 1 | Fuelwood use, prroduction, land use change are assumed driven by caloric needs | None | None | None | Model simulated for 25 years. No specific stability metrics are reported. |
| Hoddinott et al. (2012) | Assessed the impact of the Productive Safety Net, Other Food Security and Household Asset Building Programs on food security, assets, and agricultural production | Statistical | No, Type 1 | Grain production and yields, households' agricultural investments, use of fertilizer | Production and yields | None | None | Not dynamic, although data for multiple years are analyzed. |
| Holden and Shiferaw (2004) | Bioeconomic model of a less-favored area in the Ethiopian highlands to analyze the relationships between population pressure, poverty, and land degradation, and to test policies for reducing vulnerability and improving sustainable management of the resource base. | Optimization | Yes, Type 3 | Net food surplus/deficit in days per year | Yields or production | None | None | Reports annual outcomes for five years. No specific stability metrics reported. |
| Holden et al. (2005) | Similar to Holden and Shiferaw | Optimization | Yes, Type 3 | Net food surplus/deficit in days per year | Yields or production | None | None | Simulates 10 outcomes per year for 5 to 10 years. No specific stability metrics reported. |
| Hussien et al. (2017) | Analyzes water-energy-food interactions in Iraq | Simulation, integrated | No, Type 3 | Water use to support food consumption | None | None | None | Simulates annual values for 35 years. No specific stability metrics reported. |
| Ibrahim et al. (2009) | Analysis of the food security status of farming households as well as optimization of farm plan to improve food security | Optimization | No, Type 4 | Household caloric intake | Caloric intake | None | None | Not dynamic |
| Inder et al. (2017) | Livelihood strategy choices and child welfare, Zambia | Statistical | No, Type 2 | calories as % of minimum threshold | Caloric intake | None | None | Not dynamic |
| Islam et al. (2018) | Farm diversification and food security, Bangladesh | Statistical | No, Type 2 | HDDS; WDDS; food variety score (FVS) | None | Food insecurity scale | None | Uses panel data from 2011/12 and 2015 for analysis but not dynamic model. |
| Joshi and Joshi (2017) | Assesses household food security outcomes in mountain regions of Nepal | Statistical | No, Type 2 | FIVIMS framework, per capita edible food grain availability; per capita caloric intake | Caloric availabiility or intake | None | None | Not dynamic |

(continued on next page)

| Reference | Setting | Model Classification | Agricultural Systems Model and Type of Analysis[a] | Key reported indicators | Availabiliy Indicators | Access Indicators | Utilization indicators | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| Kabura Nyaga and Doppler (2009) | Linkages between cash crops and food security in Murang'a District, Kenya | Statistical | No, Type 2 | Food security index that represents a particular household's food security status in relation to all other households in the sample. | None | None | None | Not dynamic |
| Kaminski and Thomas (2011) | Examines the impact of institutional changes in the cotton sector on the evolution of smallholders 'land-use decisions | Optimization | No, Type 1 | Uses food security goal as determinant of land-use decisions | None | None | None | Not dynamic |
| Karki et al. (2015) | Examines rural household food self-sufficiency in Nepal to assess pathwyas to improved food self-sufficiency | Statistical | No, Type 3 | Household food self sufficiency | None | None | None | Not dynamic |
| Kassie et al. (2015) | Examines food security and gender in Malawi using order probit model with agricultural explanatory variables | Statistical | No, Type 4 | subjective/self-reported food security | None | Food insecurity scale | None | Not dynamic |
| Kassie et al. (2008) | investigated the impact of stone bunds on value of crop production per hectare in the Ethiopian highlands | Statistical | No, Type 1 | Crop yields | Yields or production | None | NOE | Not dynamic |
| Kokoye et al. (2013) | Optimization of allocation of resources to different crops in the cotton zone in the Northern region of Benin (West Africa). | Optimization | No, Type 1 | Area cultivated per crop; gross margin per crop | Yields or production | None | None | Not dynamic |
| Kowero et al. (2005) | Analyzes how economic development goals in Southern Africa that seek to increase rural incomes, food security and environmental stability can be reconciled in the context of a set of activities and constraints on land, labor, food production, access to forest and other resources. | Optimization | Yes, Type 1 | Food self sufficiency; crop production | Yields or production | None | None | Not dynamic |
| Laborte et al. (2007) | This paper illustrates the use of a multi-scale method enabling assessment of multi- purpose natural resource management options. Three examples of analyses are presented for Ilocos Norte province in the Philippines, at the farm household, municipal (Batac municipality) and provincial levels. | Optiimization | Yes, Type 3 | Crop yield, gross margins, net margins | Yields or production | None | None | Not Dynamic |
| Laborte et al. (2009) | In this paper, a farm household model is used to evaluate the potential attractiveness to farmers in the northernmost province of the Philippines, Hocos Norte, of the three innovative production technologies mentioned earlier, HYR, BFS, IPM, and ofsite-specific nutrient management (SSNM) | Optimization | Yes, Type 3 | Crop yield, gross margins, net margins | Yields or production | None | None | Not dynamic |
| Lázár et al., (2015a) | Examines agricultural livelihoods, climate change and food security in Bangladesh | Simulation, integrated | Yes, Type 4 | Caloric intake; hunger periods | Caloric availabiility or intake | None | None | Simulated monthly outcomes for 2014 to 2050. Reports the number of months with average caloric availability less than a threshold. |
| Leonardo et al. (2018) | Agricultural household model used to connect consumption/production sides for small-holders, evaluate tradeoffs in policy objectives | Optimization | Yes, Type 4 | Maize self-sufficiency; maize sales | Yields or production | None | None | Not dynamic |

| Reference | Setting | Model Classification | Agricultural Systems Model and Type of Analysis[a] | Key reported indicators | Availabiliy Indicators | Access Indicators | Utilization indicators | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| Louhichi and Gomez y Paloma (2014) | Household level analysis of agricultural policies and food security in Sierra Leone, emphasizing rice subsidies | Optimization | Yes, Type 3 | Crop yields | Yields or production | None | None | Not dynamic |
| Maatman et al. (1998) | A linear programming (LP) model for a farm household, representative for farm households on the Central Plateau of Burkina Faso | Optimization | Yes, Type 2 | Food surplus or deficit in % of energy requirement | Caloric availabiility or intake | None | None | Not dynamic |
| Magcale-Macandog et al. (2010) | Understanding of the role of agroforestry in ensuring food security of farming households in the Philippine uplands. | Simulation, biophysical | Yes, Type 3 | Adequacy of farm harvest to meet basic household needs & months with food abundance and scarcity/hunger; Food expenditure and household income | Caloric availability or intake | None | None | Simulated annual outcomes for 9 years. No specific stability metrics reported. |
| Marsh et al. (2016) | Estimated elasticities between specific ag technology (vaccinations) and food consumption expenditures | Statistical | No, Type 2 | Food consumption expenditures | None | Consumption | Non | Not dynamic |
| Modi (2015) | Uses agricultural variables as determinants of food security in South Africa | Statistical | No, Type 2 | Food security value (own designed index of yields and consumption) | None | None | None | Not dynamic |
| Molua (2012) | Evaluated household-level food security risks associated with climate variation, and how households respond to these risks in a patriarchal society such as in Northern Cameroon | Statistical | No, Type 1 | Food availability;Income expenditure on food according to season;Proportion of food sources in household diets | Caloric availability or intake | Consumption | None | Not dynamic |
| Murungweni et al. (2011) | Evaluated characteristics and drivers of rural livelihoods in the Great;Limpopo Transfrontier Conservation Area in southern Africa to assess the vulnerability of inhabitants to the different hazards they face | Simulation, integrated | No, Type 1 | "food in household"; "cash in household" | Caloric availability or intake | None | None | Not dynamic |
| N'Danikou et al. (2017) | Examined rural-to-urban continuum of households, focus on agrobiodiversity | Statistical | No, Type 2 | Food security self-assessment | None | Food insecurity scale | None | Not dynamic |
| Niragira et al. (2015) | Crop patterns and food security thresholds, Burundi. Optimizing across 15 different crops for best food security outcomes | Optimization | Yes, Type 3 | Macronutrient self-sufficiency | Caloric availability or intake | None | None | Not dynamic |
| Nkegbe et al. (2017) | Assessee impact of 'Feed the future' program, ag system, Ghana | Statistical | No, Type 2 | HH Hunger Scale | None | Food insecurity scale | None | Not dynamic |
| Obayelu and Onasanya (2016) | Evaluated the relationship between biodiversity and food sedurity in Nigeria | Statistical | No, Type 2 | Calories consumed | Caloric availability or intake | None | None | Not dynamic |
| Ogot et al., (2017a) | Evaluated the relationship between farm technology adoption and child nturitional outcomes in Kenya | Statistical | No, Type 2 | HDDS, food expenditure, anthropometry | None | Consumption, Food insecurity scale | Anthropometry | Not dynamic |
| Qun'ou et al. (2012) | Assess the key factors affecting food security between 1981 and 2005 using panel data model includes cross-sectional and time-series information related to the factors influencing food security and the indicators used to measure food security. | Statistical | No, Type 3 | Grain production per capita | Yields or production | None | None | Panel data from 1981 to 2005, but not explicitly dynamic. No specific stability indicators reported. |
| Radchenko and Corral (2018) | Examined the impact of commercialization on food security of agricultural households | Statistical | No, Type 4 | Food expenditures | None | Consumption | Non | Not dynamic |

| Reference | Setting | Model Classification | Agricultural Systems Model and Type of Analysis[a] | Key reported indicators | Availabiliy Indicators | Access Indicators | Utilization indicators | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| Rader et al. (2009) | Agricultural risk decision support system for resource-poor farmers in Burkina Faso, West Africa. Optimization of crop planting practices to maximize household income and minimize food deficit subject to climate forecasts. | Optimization | Yes, Type 4 | caloric deficit of a household | Calorific availability or intake | None | None | Not Dynamic |
| Ragasa and Mazunda (2018) | Estimated impact of farm input subsidies on food security in Malawi using agricultural household model. | Statistical | No, Type 2 | HDDS, FVS (Food Variety Score), FCS, Crop yields | Yields or production | Dietary diversity | None | Used panel data from 2010 and 2013. No specific stability metrics reported. |
| Reincke et al. (2018) | Assessed whether smallholder farmers in two districts of Tanzania benefitted from cassava production | Statistical | No, Type 2 | HFIAS, DDS, Availability index (AVIN) | Calorific availability or intake | Food insecurity scale, Dietary diversity | None | Not Dynamic |
| Rigolot et al. (2017) | Climate policies in mixed crop-livestock systems, Burkina Faso | Simulation, Integrated | Yes, Type 4 | Yields, income, dietary energy production | Yields or production, Calorific availability or intake | None | None | Simulates baseline and 2050 climate with different interventions, compares distributions of caloric availability to household requirements. |
| Salazar et al. (2016) | Examined 'pathways' linking agriculture and food security for smallholder farmers in Bolivia | Statistical | No, Type 2 | Crop production, income, FAO food security index, food consumption | Yields or production, Calorific availability or intake | Food insecurity scale | None | None |
| Sassi and Cardaci (2013) | Analysis of the impact of the likely change in rainfall on food availability and access to food in Sudan. | CGE | No, Type 3 | Food production, price and availability. Household income | Yields or production | None | None | Not Dynamic |
| Seaman et al. (2014) | Impact of climate change on poverty and food security in developing countries, using entitlement theory approach | Simulation, other | No, Type 2 | Income, crop production, nergy balance | Caloric availability or intake; Yields or production | None | None | Not Dynamic |
| Sibhatu et al., (2015a) | Production diversity and dietary diversity for small farms in sub-Saharan Africa and India | Statistical | No, Type 2 | Food production diversity, food variety diversity | Yields or production | Dietary diversity | None | Not Dynamic |
| Stephens et al. (2012) | investigation of interactions between natural resource-based poverty traps ad food security in highland Kenya. | Simulation, Integrated | Yes, Type 4 | Availability, Access | Yields or production | Consumption | None | Simulated for 100 quarters, consumption shorfalls reported over time but no specific stability metrics |
| Suneetha and Yirgu (2010) | The Household Food Balance Model was used to quantify the net available food for rural households, and to examine the statistical association of sixteen independent household variables with household food availability | Statistical | No, Type 2 | Proportion of shortfall/surplus of the average daily dietary energy intake | Caloric availability or intake | None | None | Not dynamic |
| Szabo et al. (2016) | Examined linkages between soil quality and food security in Bangladesh | Statistical | No, Type 2 | Food expenditure, HH calorie availability | Caloric availability or intake | Consumption | None | Not Dynamic |
| Tesfaye et al. (2008) | Evaluated the impact of small-scale irrigation on household food security based on data obtained from 200 farmers in Ada Liben district of Ethiopia in 2006 | Statistical | No, Type 2 | Reported food shortages, food expenditure, Coping Strategy Index (CSI) | None | Consumption | None | Not Dynamic |
| Thorlakson and Neufeldt (2012) | Examined how agroforestry techniques can help subsistence farmers reduce their vulnerability to climate change in Kenya. | Statistical | No, Type 2 | Food production, coping strategies to deal with shocks | Yields or production | None | None | Not Dynamic |

| Reference | Setting | Model Classification | Agricultural Systems Model and Type of Analysis[a] | Key reported indicators | Availabiliy Indicators | Access Indicators | Utilization indicators | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| Thornton et al. (2006) | Analyzed effects of subdivision and land fragmentation on household livestock numbers and on food security in pastoralist communities in Kenya | Simulation, Integrated | Yes, Type 4 | Cash flows, calories | Caloric availability or intake; yields or production | None | None | Simulated annual outcomes for 24 years based on 1977 to 2000. No specific stability metrics reported. |
| Tingem et al. (2008) | Evaluated the potential of using dry/wet year predictions to reduce risk in subsistence agricultural production associated with climate variability at the site level. | Simulation, Biophysical | Yes, Type 3 | Crop yields | Yields or production | None | None | Evaluates outcomes for growing seasons under alternative assumptions. No specific stability metrics assessed. |
| Tittonell et al. (2009) | investigated current differences in resource use efficiencies and degree of crop-livestock interactions across farm types; and impact of different interventions in different farm types. | Simulation, Biophysical | Yes, Type 3 | Crop yields, energy requirements | Caloric availability or intake & yields or production | None | None | Simluated for 20 growing seasons. Caloric availability compared to household requirement. |
| Traore et al. (2017) | Assessed climate risk for cereal crops in APSIM | Simulation, biophysical | Yes, Type 3 | Crop yields, self sufficiency | Yields or production | None | None | Simulated annual values from 1970 to 2070 for some variables and compared 2040–2069 to 1980–2009 baseline. No specific stability metrics reported. |
| Traoré et al. (2018) | Association of cattle of different breeds to household food security in southern Mali | Statistical | No, Type 2 | HDDS, FCS, mHFIAS | None | Food insecurity scale, Dietary diversity | None | Not dynamic |
| Waithaka et al. (2006) | Objective was to improve understanding of farmers' conditions through the use of participatory approaches that incorporated simulation modeling, with a focus on farmer learning. | Simulation, Integrated | Yes, Type 3 | Crop prices, farm income, ideal farm perceptions | None | None | None | Not Dynamic |
| Walker and Schulze (2006) | Investigated sustainability at the smallholder agro-ecosystem level in KwaZulu-Natal. Agroecosystem sustainability was assessed in regard to yield, soil organic carbon and nitrogen responses to a range of management practices and plausible climate scenarios. | Simulation, Biophysical | Yes, Type 3 | Crop yields | Yields or production | None | None | Modeled 49 growing seasons. No specific stabiility metrics reported. |
| Wane et al. (2017) | Porter's value chain model applied to milk, with discussion of and implications on food security and a focus on gender. | Statistical | No, Type 2 | Food insecurity scale (HFIAS) | None | Food insecurity scale | None | Not Dynamic |
| Whitney et al. (2017) | Assessed the impact of government policy supporting home gardens on food security in Uganda | Simulation, Biophysical | Yes, Type 3 | Crop yields, Nutrient content of specific foods vs. Dietary Reference intake | Caloric availability or intake; yields or production | None | None | Not Dynamic |
| Wichern et al. (2017) | Data from 1927 households from the World Bank Living Standards Measurement Study were used to estimate the calorific contribution of livelihood activities to food availability in Uganda. | Other | No, Type 2 | Food energy per capita, food self-sufficiency from own production | Caloric availability or intake | None | None | Not dynamic |
| Wineman and Crawford (2017) | Assessed the impacts of climate change on crop choice in Zambia. | Optimization | Yes, Type 3 | Crop yields, calorie production from field crops | Caloric availability or intake; yields or production | None | None | Reports outcomes for year 2050 but not explicitly dynamic |

(*continued*)

| Reference | Setting | Model Classification | Agricultural Systems Model and Type of Analysis[a] | Key reported indicators | Availabiliy Indicators | Access Indicators | Utilization indicators | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| Winter et al. (2015) | Examines jatropha value chain development and food security spillovers. Model optimizes assuming income sufficient for minimum nutrition standards from FAO. | Optimization | Yes, Type 4 | Household income, protein and energy balance | None | None | None | Monthly model over short time horizon. No stability metrics analyzed. |
| Wossen et al. (2018) | Evaluated possible impacts of farm level adaptation strategies to climate change | Simulation, Integrated | Yes, Type 4 | Crop yields, calorie production from field crops, allocation of income to food consumption | Caloric availability or intake; yields or production | Consumption | None | Simulated annual values for 15 years. No specific stability metrics reported. |
| Yiridoe et al. (2006) | Farm optimization model used to assess the economic implications of introducing an improved fallow rice cropping system in Northern Ghana. | Optimization | Yes, Type 4 | Gross margins, Household nutrition energy requirements, Self-sufficiency in fod production | Yields or production | None | None | Not Dynamic |
| Zereyesus et al. (2017) | Examined off-farm labour and food security outcomes in Northern Ghana. | Statistical | No, Type 2 | Household Hunger Scale (HHS) Expected future food expenditure, predicted food shortfall from poverty line | Caloric availability or intake | Food insecurity scale | None | Not dynamic |
| Zheng et al. (2009) | Regression trees were used to predict yield responses from soil and agronomic variables from all fields, and classification trees were used to identify the most important soil and management variables affecting yield | Statistical | No, Type 2 | Crop yield, yield variability | Yields or production | None | None | Not Dynamic |

[a] **Type 1** is Analyses that are food security motivated, but food security itself is not modeled, **Type 2** includes papers with One or more metrics representing a component of food security are analyzed as a function of a limited number of agricultural system level variables, **Type 3** are Analyses with an agricultural system model and prediction of some indicator of food security status, and **Type 4** is More integrated biophysical or agricultural system modeling at the household level that considers both agricultural and food security outcomes.

## Appendix D. Listing and description of 26 regional models reviewed

| Reference | Setting | Model Classification | Agricultural Systems Model? | Key Reported Indicators | Availability Indicators | Access Indicators | Utilization Indicator | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| Akter and Basher (2014) | Impacts of food price and income shocks on household food security and economic well-being in low-income rural communities in 12 districts of Bangladesh. | Statistical | No | Self-reported food security during previous three years from a single-visit recall data single survey in 2009/10. | None | Food insecurity (experiential scale) | None | Shows the percentage distribution of the worst months reported during each of the three years. |
| Antle et al. (2014) | Sub-Saharan Africa: declining agricultural productivity and persistence of high poverty levels. Case example is from Machakos, Kenya. | Economic simulation | Yes | Proportion of farms below a income-based poverty line | None | None | None | None |
| Bakker et al. (2018) | Food insecurity is a complex phenomenon with biophysical, climatic, economic, and infrastructure facets. Proof-of-concept is a simplified representation for Ethiopia. | Other simulation | Yes | Utility-maximizing food consumption by household member and converts this into estimated caloric intakes, which are characterized as a 'utilization and health' outcome. | National or regional production, Net imports | Household food consumption | Inidividual food consumption, individual caloric intake | Results provided over 72-month time horizon, with analysis of a yield shock. No specific assessment of stability is provided. |
| Chavez et al. (2015) | Integrates current understanding of the various interacting systems of climate, crops and the economy to determine short- to long-term risk estimates of crop production loss, in different climate and adaptation scenarios. Application to provinces north and south of the Yangtze River in China. | Biophysical simulation | Yes | Maize and rice yields | Crop yields | None | None | None; analysis provides distributions based on time series data, but is not explicitly dynamic. |
| Cheng et al. (2015) | Analysis of four water resource utilization plans and three "climate conditions" in Heilongjiang Province, China. | Other simulation | Yes | Per capita grain production | Per capita production | None | None | Data from 2003 to 2010 are used to develop the model and predictions for 2020 are reported. The model is dynamic, but it is not clear what time units (annual) or how years are linked. |
| Cordero-Ahiman et al. (2017) | Determinants of food insecurity among the indigenous communities of the Sierra Tarahumara in Mexico. | Statistical | No | Latin American and Caribbean Household Food Security Measurement Scale (ELCSA). | None | Experience-based food (in) security scale | None | Not dynamic |
| Dermody et al. (2018) | A modeling framework for capturing regional and sectoral interdependencies and cross-scale feedbacks in the global food system that contribute to emergent water use patterns. | Conceptual | No | No specific metrics of food security are specified but the authors appear to use food production as representing this. | National or regional production | None | None | No data and only implicit dynamics |
| Djebou et al. (2017) | Compares and examines the relationships among agricultural assets, incomes and food security in rural communities of Ghana, Senegal, and Liberia. | Statistical | No | Experience-based food insecurity scale with five questions that has some overlap with the type of questions in FIES. If 2 were answered | None | Experience-based food (in) security scale | None | Not dynamic |

(*continued*)

| Reference | Setting | Model Classification | Agricultural Systems Model? | Key Reported Indicators | Availability Indicators | Access Indicators | Utilization Indicator | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| | | | | positively, household was considered "food insecure". | | | | |
| Dorosh et al. (2016) | This article examines options for enhancing food security in South Sudan, focusing mainly on ways to maintain availability of cereal supply and price stability. | Partial equilbrium | No | Aggregate cereal production and consumption | National or regional production | National or regional consumption | None | Not dynamic |
| Guillaume et al. (2014) | Macro-level generic conceptual model | Conceptual | No | Food supply and demand and their differences at a conceptual level | None | None | None | Not dynamic |
| Haggblade et al. (2017) | This paper develops a multi-market simulation model to evaluate the impact of common production and world-price shocks on food consumption of vulnerable groups in Sahelian West Africa. | Partial equilbrium | No | Aggregated consumption ("demand") in kg/capita/day for five food categories by household types, also converted to calories per capita per day. | National or regional production | National or regional consumption | None | Not dynamic |
| Harttgen et al. (2016) | A very simple micro-based simulation approach to analyze how changes in prices of specific food groups, such as maize prices or prices for staple foods, as well as how negative short-term household level income shocks affect the entitlements to calorie consumption of individuals and how these changes affect overall food poverty. | Economic simulation | No | Consumed calories per capita per day are computed and compared with age and sex specific energy requirements to determine "food poverty" | None | Per capita calories consumed | None | Proportion of households in food poverty reported for 13 months, but most results are probability distributions of outcomes without reference to intertemporal changes |
| Larson et al. (2014) | A rational expectations model of competitive storage and trade, based on wheat markets for the Middle East and North Africa and the rest of the world. We use the model to quantify the effects of a strategic inventory policy designed to protect consumers in the region from very high prices. | Other simulation | No | Coefficienct of variation for prices | None | None | None | The analysis is dynamic, but the focus is on variability metrics, not intertemporal outcomes |
| Lázár et al. (2015) | This study is based on the south-western coastal zone of Bangladesh, where there is a tidal infuence. Here an integrated approach has been proposed to develop a simulation model to support agriculture and poverty-based analysis and decision-making in coastal Bangladesh. | Integrated simulation | Yes | The number of months in a year when household calorie intake is less than 1805 kcal per capita per day. Caloric intake appears to be based on a relationship with household income. | Household food production | Household calories consumed | None | Model is simulated for 60 years, but no specific stability metrics are discussed. |
| Lloyd et al. (2011) | Model estimating future undernutrition that accounts for food and nonfood (socioeconomic) causes that can be linked to available regional | Other simulation | No | Caloric availability is modeled and then converted to an estimate of underweight and stunting, with a relationship | National caloric availability | None | Proportion underweight, proportion stunted | Model focuses on a single future year (2050) without clearly specified dynamics |

(*continued*)

| Reference | Setting | Model Classification | Agricultural Systems Model? | Key Reported Indicators | Availability Indicators | Access Indicators | Utilization Indicator | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| | scenario data. We estimated child stunting attributable to climate change in five regions in South Asia and sub-Saharan Africa (SSA) in 2050. | | | assumed to be stable through 2050. | | | | |
| Mainuddin et al. (2011) | Examines the impact of climate change on rice production in the lower Mekong Basin, evaluates some widely used adaptation options, and analyses their implications for overall food security by 2050. | Biophysical simulation | Yes | Rice yields and production per capita | Crop yields, per capita production | None | None | Analysis uses dynamic models but intertemporal results are not reported and no stability metrics are assessed |
| Mason-D'Croz et al. (2016) | Scenarios for southeast Asia developed by regional stakeholders and quantified using two global economic models, GLOBIOM and IMPACT, in interaction with stakeholder-generated narratives and scenario trends (similar to 2017 paper) | Integrated simulation | Yes | Kilocalories per ha (Fig. 4) Per capita domestic kcal availability (Fig. 4) Total crop production, MT, 2020 to 2050, one observation per decade (Fig. 7) Rice and sweetpotato yields (timing as above; Figs. 8 and 9) Regional kcal availability, years 2020 to 2050 (Fig. 10) | Crop yields, per capita caloric availability | None | None | Dynamic analyses from 2020 to 2050 but no clear stability metrics |
| Montella et al. (2015) | FACE-IT is a new IT infrastructure designed to accelerate existing disciplinary research and enable information transfer among traditionally separate fields. | Other | No | Compares crop yields from different simulation models | Crop yields | None | None | Models are dynamic but intertemporal results are not a focus and no stability metrics assessed |
| Moore et al. (2012) | Food security and climate change. Focused on the East African countries of Kenya, Uganda, Tanzania, Burundi, and Rwanda | Biophysical simulation | Yes | Maize yields | Crop yields | None | None | There is some underlying dynamic element, although the results show only changes from 2000 to 2009 and 2050–2059. |
| Oehmke et al. (2018) | Stylized African agricultural development setting | Other simulation | No | Stylized game theory payoffs, none empirically based | None | None | None | Dynamics are implied by repeated games that represent crop years, but intertemporal results are not a focus and no stability metrics assessed |
| Paeth et al. (2008) | Assessment of future crop yields and production in Benin | Other simulation | Yes | Crop yields | Crop yields | None | None | Projections of production and yields are made through 2020 at five-year intervals, not stability metrics assessed |
| Palazzo et al. (2017) | Scenarios for West Africa developed by regional stakeholders and quantified using two global economic models, GLOBIOM and IMPACT, in interaction | Integrated simulation | Yes | Crop yields (gigacalories per ha; Fig. 4) Relative change in crop yields (Fig. 6) Percent deviation in kcal availability | Crop yields, Caloric availability per capita | None | None | Dynamic analyses from 2020 to 2050 but no clear stability metrics |

(continued)

| Reference | Setting | Model Classification | Agricultural Systems Model? | Key Reported Indicators | Availability Indicators | Access Indicators | Utilization Indicator | Dynamics or Stability Dimension |
|---|---|---|---|---|---|---|---|---|
| | with stakeholder-generated narratives and scenario trends and SSP assumptions. | | | per capita per day (Fig. 7) | | | | |
| Springmann et al. (2016) | The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), is used as input for a comparative risk assessment of changes in fruit and vegetable consumption, red meat consumption, and bodyweight | Integrated simulation | Yes | National food availability was converted to a consumption estimate using waste and edible portion | National or regional production, Net imports | National or regional consumption | None | Model focuses on a single future year (2050) without clearly specified dynamics |
| Tabeau et al. (2017) | Impact of REDD policies on the agri-food sector and food security with a global CGE model called MAGNET using a scenario approach. It focuses on the restrictions on agricultural land expansion within the REDD policy package. | Economic simulation | No | Availability is a production index, access is an index of per capita consumption | National or regional production | National or regional consumption | None | The models are driven by underlying dynamics, but intertemporal patterns are not reported, only results for 2030 |
| Wailes et al. (2015) | Examined increased production and self-sufficiency as a means to address food insecurity in West Africa, noting that "The food security objective of CARD is to double rice production in West Africa by 2018" | Partial equilbrium | No | Aggregate production at national level, per capita rice consumption | National or regional production | Per capita food consumption, National or regional food consumption | None | Not dynamic |
| Wu et al. (2016) | A multidimensional coupling assessment index system and model, and carries out assessment of the food security level and the warning status of China between 1995 and 2012. Elements of the index include quantity coordination, structural coordination and regional coordination. | Statistical | No | The index of coordination is taken to be a sort of indicator of food security, but it is not consistent with other measures and should be considered only an intermediate "system function" type indicator, given that its correlation with other more specific indicators is not done. | None | None | None | Shows coordination index values for years 1995 to 2012, but no specific stability metrics |

## Appendix E. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2020.103028.

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