Conceptual frameworks linking agriculture and food security: a review and recommendations for improvement

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Abstract

Many conceptual frameworks have been developed to facilitate understanding and analysis of the linkages between agriculture and food security. Despite having usefully guided analysis and investment, these frameworks exhibit wide diversity in perspectives, assumptions and application. This paper examines this diversity, providing an approach to assess frameworks and suggesting improvements in the way they are specified and applied. Using criteria based systems modelling conventions, we evaluate 36 frameworks. We find that many frameworks are developed for the purpose of illustration rather than analysis and do not clearly indicate causal relationships, tending to ignore the dynamic (stability) dimensions of agriculture and food security and lacking clear intervention points for improving food security through agriculture. By applying system modelling conventions to a widely used framework, we illustrate how such conventions can enhance a frameworks' usefulness for overall illustration purposes, delineation of hypotheses on agriculture-food security links, and examining potential impacts of interventions.

Main

With increased attention in recent years by governments and the global development community on understanding the role of agriculture and food systems in achieving food security, research communities in both fields have focused more intently on understanding the linkages between agriculture and food security outcomes. This has resulted in the creation of many distinct conceptual frameworks linking agriculture and food security, which often form the basis for setting research and policy objectives or priorities. Such frameworks represent the relationships between agriculture and food security with combinations of relevant theories and concepts from a wide range of academic fields that engage with either agriculture, food security or both. Although these frameworks have understandably disparate purposes and content, and are undoubtedly useful in many contexts, the lack of standardization and clarity of their diagrammatic representations may imply a limit on their usefulness. As proposed by Béné et al.[1] "*the shift toward sustainable food systems should be accompanied by a more appropriate conceptualization, one that presents food system as complex, heterogeneous over space and time and replete with linear and non-linear feedbacks.*"

Principles and criteria from systems thinking and modelling provide a relevant means for assessing and improving the frameworks that link agriculture and food security. Systems thinking and modelling tools can improve understanding of the causal factors linking agriculture to food security outcomes as well as address dynamics and non-linearities. These tools facilitate the representation and integration of complex interacting factors that can limit the effectiveness of interventions and create unintended side effects, including in public health[2].

Despite the clear affinity between systems modelling and conceptual frameworks linking agriculture to food security outcomes, there are few published applications exploring this link[3]. However, the field of systems modelling has a history stretching back more than six decades, and many of these tools are well-developed and appropriate for the development of conceptual frameworks. The potential benefits of wider use of systems modelling tools for conceptual framework development among many disciplines that contribute to knowledge of food security outcomes motivates our focus on those tools herein.

Our principal objective is to suggest approaches drawing on systems modelling that can improve the clarity and usefulness of conceptual frameworks that link agricultural production to food security outcomes. This includes specifying evaluation criteria for conceptual frameworks linking agriculture and food security, with an emphasis on the application of well-developed tools and concepts from systems modelling; evaluating existing conceptual frameworks using these defined criteria; and finally illustrating the modification of an existing framework to better align with systems modelling conventions. By raising awareness of the applicability of systems modelling principles and tools to food security analyses, and by reinforcing a definition of food security that goes beyond production and calories, we aim to improve the robustness, conceptual soundness, applicability, and comparability of frameworks for agriculture and food security in ways that reach across and unite researchers from various disciplines working in this area.

A number of definitions and delineations are relevant to stating these objectives more precisely. First, we apply a broad definition of a "conceptual framework" and include any discussion or diagram that describes or represents hypothesized pathways linking agricultural production and food security, whether or not that is a principal objective. Second, following the internationally accepted definition, we consider four dimensions of food security in our assessment: availability, access, utilization and stability[4,5]. Finally, we focus on the nature of the conceptual representations (e.g. how diagrams are constructed to represent hypothesized pathways) rather than on their specific content. We recognize that different purposes and perspectives require different content; a diagram focusing on how increased livestock production affects food security outcomes would have different pathways than one focusing on the impacts of increases in the production of horticultural crops. However, food security is itself a complex concept, with multiple underlying components and potential metrics. Thus, it will often be appropriate to disaggregate the representation of conceptual frameworks into multiple components (availability, accessibility, utilization and stability).

To identify the conceptual frameworks to be assessed, we undertook a SCOPUS search with the terms "food security conceptual framework", which returned 447 documents. These citations were reviewed for appropriateness for our purposes and supplemented with other frameworks previously known to the authors. This yielded 36 frameworks (Supplementary Table 1). We included all frameworks showing linkages between agriculture and food security, although not all frameworks had those linkages as a focal point. We first characterized the frameworks by their principal intended purpose (Table 1), using our judgment about the purpose if this was not explicitly stated and recognizing that a framework may have multiple purposes.

We then assessed the frameworks through the lens of systems thinking and modelling tools (Table 2), particularly those diagramming practices used in system dynamics[6]. System Dynamics (SD) is a method used to understand the origins of behaviours considered problematic and to identify potential solutions that will result in sustained improvement. It applies systems control theory to social and economic systems, with an emphasis on stock-flow-feedback processes. SD provides a set of conceptual and computational tools to enhance learning in complex systems through incorporation of knowledge from multiple disciplines. This can help to identify the most effective actions that will result in sustained improvement of specific outcomes[2]. These tools emphasize the delineation of clear model boundaries relevant to understanding what is endogenous, exogenous or excluded from a conceptual model. This facilitates the analysis of the stability dimension of food security, which often receives limited emphasis in conceptual analyses of food security[3].

Diagramming tools in SD delineate stocks (accumulations or observable states) and flows (variables resulting in changes to stocks), the polarity of individual causal linkages (positive or negative indicating whether changes in a causal variable result in changes in the same or opposite direction in the resulting variable), and depict feedback processes and their polarity (positive polarity reinforcing change, or negative polarity dampening change). Because SD conceptual or empirical models aim to understand how to improve outcomes, diagrams often indicate key points for intervention and actors whose decisions are key to their implementation.

We also describe the level of analysis (e.g. national, regional, household, intra-household) used in the conceptual frameworks. Different food security components are often—but not always—aligned with different levels (e.g. availability is more frequently considered at a national, regional or community level, access at a household level, utilization at an intra-household level). In addition, we assess the specificity of the food security indicators as it relates to the purpose and principal pathways examined in the framework. Generally, frameworks are used to examine specific aspects of agriculture-food security linkages. Consequently, they can define outcomes more specific than just 'food security' because they can identify interactions and indicators for the different linkages and pathways and relate them to the principal pillars of food security (availability, access, utilization and/or stability). For example, biophysical linkages with crop yields might be emphasized for availability, while income might receive more emphasis for access.

Table 1 about here

Table 2 about here

To achieve the third objective, we selected one framework – a diagram originally presented in Heady et al.[7] and subsequently adapted by Kadiyala et al.[8]. We evaluated it using the criteria in Table 2 and applied the systems thinking and modelling conventions discussed above to illustrate the process and potential usefulness of a systems modelling approach.

Existing Frameworks

Conceptual frameworks can be characterized based on multiple criteria, including their purpose, indicators, scale of the analysis and principal linkage pathways (Supplementary Table 1). Here we critique the relative consideration given within the current state of practice to the following dimensions: framework purpose; model boundaries; feedback processes and dynamics; actors and decisions; levels of aggregation; intervention entry points; food security indicators. By looking at these characteristics within framework diagrams, we can assess the extent to which different frameworks enhance logical rigor, clarify our understanding of causal linkages and facilitate the development of quantitative analyses of impact pathways between agriculture and food security.

Framework Purpose The purposes of conceptual frameworks include exposition (illustration), summarizing empirical evidence and enhancing logical rigor. Frameworks that focus on food security and specify pathways linking agriculture to outcomes include those presented in Kadiyala et al.[8], Randolph et al.[9], Dobbie and Balbi[10], Garrett[11], Kanter et al.[12] and Sassi[13]. The illustrative pathways in these frameworks suggest more directly the mechanisms (variables and relationships) by which agricultural systems outcomes and food security outcomes are linked. Many other frameworks are quite high-level and describe very general relationships rather than specific pathways. The ShiftN[14] food system diagrams have a greater level of complexity and begin to delineate pathways, but do not focus specifically on food security.

For the vast majority of conceptual frameworks, the main purpose is exposition, i.e. the frameworks visualize concepts and linkages to facilitate reader understanding of text descriptions. One-third of the reviewed frameworks complement exposition with evidence summary. Only six frameworks fall into the logical rigor category, and even fewer use the conceptual frameworks to describe either the design or computations for focused[10,15] or integrated assessment models[16].

Model Boundaries

Model boundaries define what is endogenous, exogenous or excluded for the purposes of the (conceptual or quantitative) analysis. In many frameworks, the boundaries are not clearly delineated. *Context* or *environment* variables (we use italicized text for terms used in the frameworks) appear to be assumed to be exogenous, and these encompass a vast variety of factors (political, social, cultural, knowledge, infrastructure, services, (macro)economic, climate, disease outbreak, policies, programs, conflicts, technology, food environments, legal systems, ethical values, productive assets and sometimes even food availability itself). As such, the frameworks often do not incorporate them explicitly into the representation nor make clear at what level or to what degree these factors explicitly engage with other elements of the framework and influence outcomes. For example, the World Food Programme Conceptual Framework of Food and Nutrition Security[17] (Supplementary Figure 1, from which many subsequent frameworks are derived) seems to indicate that all factors have equal impact at the community and household levels, and *exposure to shocks and hazards* affects all levels (implied equally).

Feedback Processes and Dynamics

Diagramming conventions used to depict feedback processes and dynamics are highly variable. Many frameworks show connecting lines (sometimes with arrows in both directions) without really indicating implied directions of causality, and only Randolph et al (in their 'Figure 2')[9] indicates polarities of hypothesized linkages. Diagrams are inconsistent in their depictions of hypothesized feedback processes, and in some cases, it is difficult to determine what is connected to what. Language is often cryptic or inconsistent among linked variables (e.g. *resources* cause *inadequate education;* UNICEF)[18]. The conventions used in "Causal Loop Diagramming" (e.g. Sterman[6]) and similar hybrid diagrams that also show stocks and flows would bring a good deal of additional clarity of meaning to these diagrams (and allow them to more clearly delineate hypothesized pathways).

Most of the frameworks do not specifically represent intertemporal dynamics or feedback processes, both of which are important to represent the stability component of food security. Stability implies a high degree of consistency in food availability, access and utilization, and is thus sometimes placed in the context of the broader concept of resilience. Some frameworks discuss general resilience concepts[4,19], but the linkages to the stability component of food security are not explicit. Burchi et al.[20] depicts stability in a framework that primarily defines the four components of food security but include suggested actions and strategies to promote stability of food availability, access and utilization. Allen and Prosperi[20] integrate resilience concepts into the frameworks proposed by Ericksen[22] and Ingram[23].

Many of the frameworks also depict a linear cause-and-effect model with limited feedbacks among system elements determining food security outcomes. Representation of feedback is relevant because food systems demonstrate feedback and interdependence within and across levels[24,25,26,27]. Appropriate representation of feedback processes is particularly useful when considering proposed agriculture-based interventions designed to improve food security outcomes. The systems modelling literature (e.g. as summarized in Sterman[6]; but cf. also Hammond and Dubé[28]) has long since noted that feedback processes, accumulation and non-linearities result in dynamic complexity, which gives rise to policy resistance (the intended effects of interventions will be delayed or largely offset) and unintended consequences (other, often negative, effects may occur in response to interventions; short-term and long-term impacts of system changes can differ). Thus, understanding and representing feedback processes will often be necessary, and provide a specific link with intertemporal dynamics.

The frameworks that do represent feedback processes tend to include only a few such linkages, and these linkages differ for each diagram. General resilience frameworks[4,19,29] tend to represent changes in high-level "states" over time. The high-level framework from Hammond and Dubé[28] indicates feedback processes (and some specific mechanisms) among the *agri-food*, *environmental* and *health/disease* components of the system that determine food security. One of the more common inclusions is feedback between the food system (or agriculture) and environmental outcomes[14,20,21,22,23,30,31]. Frameworks that focus on household assets and livelihood strategies[8,32,33] tend to link livelihood outcomes (including food security) back to increases in household assets in a reinforcing feedback loop. Similarly, the UNICEF framework[34] shows a reinforcing feedback process where lack of initial livelihood assets limits improvements in child nutritional status—with ongoing intertemporal effects.

Other frameworks focus on feedbacks between consumer decisions and the structure of food supply chains and food environments[16,35,36,37] . An extension of this concept includes when consumer decisions and related outcomes (nutritional, social, economic, environmental) are hypothesized to affect system drivers such as biophysical, environmental, technology, political, socio-cultural, and demographic factors[21,22,23,36]. More specific to food security, a number of frameworks depict interactions—if not exactly feedback—between nutrition and health outcomes[9,11,38].

Although all of the represented feedback processes are likely to be appropriate for specific purposes, the lack of consistency among the frameworks about factors, directionality, feedback and intertemporal dynamics implies challenges for effective and agreed-upon representation of these effects in frameworks linking agriculture to food security. The Randolph et al.[9] diagram is probably the most detailed and relevant of the feedback-inclusive frameworks since it provides a more detailed representation of alternative pathways (including some described elsewhere, e.g. Kadiyala et al.[8]; Gillespie et al.[38]) linking agriculture, nutrition and health in the specific context of livestock ownership.

Actors and Decisions

It is often relevant for frameworks to indicate which actors make what decisions. We consider *actors* those individuals or organisations that make decisions influencing food security outcomes. Common examples would be individuals, private businesses, government agencies and NGOs. Appropriately representing actors involves indicating which decisions they make and what information or processes are involved in reaching decisions. Many frameworks are also not particularly clear about which actors and decision processes are covered or who makes what decisions. Hawkes[39] and Hawkes et al.[37] present an Actors-Processes-Outcomes framework, but this is quite high level and *processes* include *ag inputs* that are not always clearly defined. Acharya et al.[16] includes producers, *food chain actors* and *consumers*. *Consumers* or *households* are frequently represented[11,40].

Levels of Aggregation

The level of aggregation in the reviewed frameworks (national, regional, community, household, individual) varies, with specific effects or outcomes of interest for each (the Food Insecurity and Vulnerability Information and Mapping System (FIVIMS)[41]). These levels indicate the degree of aggregation for decision making by actors or for the purposes of reporting outcomes. Overlap can exist between *actors* and *levels*, but for purposes of modeling they should be clearly defined. For example, farmers are actors (decision makers) but their actions could be represented in a framework as those of individuals, or households, aggregated by farm types in a community or single market (regional, national) supply response. Food security metrics are often reported in an aggregated manner, for example, individual food consumption at the national level[7].

The majority of frameworks depict highly aggregated or generic levels. They discuss linkages between agricultural production and food security outcomes in a general way rather than for specific levels of aggregations such as the national or household level. Few of the frameworks address intra-household food security issues, e.g. with a focus on individuals. Of the 36 frameworks reviewed, only 4 had explicit treatment of individuals with the household, focusing on children (especially for nutritional status) and women. Six frameworks implied treatment of individuals (e.g. Sassi[13] mentions *individual food and nutrition pathways*), but in general the conceptual treatment of the linkages determining intra-household food security status is limited. Although we did not search for frameworks specifically addressing intra-household allocation and outcomes, the limited treatment of this issue in more generic frameworks suggests the need to reconsider this from both the conceptual and empirical perspectives.

Intervention Entry Points

Less than half of the reviewed conceptual frameworks discuss specific entry points for interventions to improve outcomes. Frameworks that include entry points for intervention vary widely in the level of specificity and often only implicitly mention the factors assumed to be exogenous. Some refer to generic interventions such as *political and environmental groundwork*[42], *policy drivers* for nutrition, inequality, and growth[8,38], the *larger biophysical and social/institutional context*[29], components of *enabling* *processes*[43], *intervention*[44], *coping mechanisms*[13], *adaptation strategies*[16], *external factors* including government and NGOs[31], or *incentives: organizational, financial, technological, and regulatory/policy*[37,39,45]. More specific frameworks describe economic, agricultural, environmental, trade, and development policy, subsidies, price controls, regulations, taxes, tariffs and infrastructure charges[14,40,46]. De la Peña et al.[47] lists activities that could enhance outcomes and impacts in nutrition-sensitive value chains, as well as women's empowerment as mediator of impacts.

Food Security Indicators

The indicators (metrics) of food security are an important component of conceptual frameworks. Most frameworks (even some focused primarily on food security) do not include all elements of availability, access, utilization and stability. The last is most often ignored. It is also not clear if these are separate or hold some sort of hierarchy (especially the availability-access-utilization linkages). Most frameworks do not include specific indicators for food security or nutrition outcomes; it is common to have the outcome be *food security* or *nutritional status* and only a few mention specific indicators at the household level such as dietary diversity[12].

Table 3 about here

Use of Systems Diagramming Tools

Although each framework must primarily satisfy a given analytical purpose, and so there is understandable variation in detail or presentation, some general observations can be made. Kadiyala et al.[8] provides a diagram (Figure 1) and related discussion of the empirical evidence about linkages between agriculture and food security and nutrition outcomes in India. This diagram is an adaptation of the framework first presented in Headey et al[7] and further developed in Gillespie et al[38]. The Kadiyala et al framework embodies characteristics of many of the diagrams and frameworks that depict linkages between agriculture and food security and nutrition (Table 4). Its frequent citation by other authors (more than 120 times since its publication) suggests its usefulness and common acceptance. Given its comprehensiveness and clarity, it illustrates well how to apply evaluation criteria and diagramming tools from systems modelling to strengthen such frameworks. This framework describes six principal pathways linking agriculture, food security, and nutrition, and describes the empirical evidence for elements of each pathway It is one of a relatively small number of frameworks indicating at least one feedback process. It also has a very clearly stated purpose (summarizing empirical evidence) and provides implied linkages to potential interventions through policy drivers. This framework also specifies multiple indicators of nutritional outcomes and multiple levels of aggregation (national, household, intra-household).However, the model boundary could be more clearly defined (e.g. policy drivers are exogenous, but also lead to other exogenous causes such as inter-household inequality or public health factors). Likewise, the nature of the linkages and the causal direction are not always clear (does a variable positively or negatively affect outcomes for which it is presumably a causal factor?). The diagram does show one major feedback process (individual nutrition outcomes scale up to national nutrition outcomes, which improve household-level assets and income generation, further improving nutrition—a feedback loop), although it omits other feedback processes that could influence nutritional outcomes or that could be useful for a conceptual assessment of interventions. It does not explicitly link the analysis based on the diagram to the data describing outcomes over time (Figure 2), and there is limited emphasis on dynamics. The entry points for potential interventions to improve nutritional outcomes – not an explicit goal of this paper – are implied through exogenous policy drivers but without explicit pathways through which policy is hypothesized to improve outcomes.

Figure 1 about here

Figure 1. Framework from Kadiyala et al. Linking Agriculture with Nutritional Outcomes. Taken from their manuscript showing a mapping of agriculture-nutrition pathways in India.

Table 4 about here

The process of using systems modelling tools to develop a conceptual framework (especially as represented with a diagram) differs from that likely used for the development of most frameworks we reviewed and offers the possibility of improvement, especially in terms of dynamics and greater specificity. A systems modelling approach would begin by defining specific intertemporal behaviour(s) that the diagram seeks to explain. This is referred to as the "reference mode behaviour*"* and is almost always shown as a graph over time. For example, in Kadiyala et al., information on the prevalence of stunting, wasting and underweight is provided for two periods, 1998-99 and 2005-06 (Figure 2). Although in this case there are only two data points for each series – which may make the figure seem trivial – we include a line graph as an illustration of a necessary "reference mode" that will typically consist of a larger number of observations and demonstrate more complex behaviour. The reference mode is useful because it focuses the diagrammatic representation on outcomes of interest, indicates a pattern of change over time (i.e. is dynamic) and indicates a relevant time frame over which the dynamics are important.

Moreover, the reference mode illustrates a behaviour that should be possible to explain with elements of the diagrammatic representation. In this case, the diagrammed framework should be able to indicate why wasting has increased during the time period, whereas stunting and underweight have decreased nationally. From the perspective of systems modelling, it is also generally more appropriate to focus a conceptual representation on a specific behaviour or outcome of interest—rather than a "system", as is often depicted—because this facilitates the delineation of appropriate model boundaries. Model boundaries are particularly important in SD modelling because of its focus on endogenous (i.e. internally generated) drivers of observed dynamics.

Figure 2 about here

Figure 2. Potential Reference Mode Behaviours Based on Data from Kadiyala et al. (Table 1, p. 44)
Graph of stunting data over time to demonstrate how this can be used to generate a reference mode that can be used in systems models.

Once a reference mode is defined, a causal diagram that represents known or hypothesized relationships can be developed to represent the stock-flow-feedback processes that generate the observed behaviour. A major premise of SD modelling is that a system's behaviour (outcomes over time) arises from its "structure", meaning the interactions among system elements that can be represented in terms of stocks (accumulations or observed states), flows (variables or relationships that change stocks) and feedback processes (a series of causal linkages that form a loop). Standard practice for the development of diagrams includes 6 major points (Box 1). The point on causality merits additional comment, given that linkages in conceptual frameworks may be based on statistical associations and even correlations. In much systems modelling work (including SD models), it is considered important to represent causal linkages rather than correlations, even if the nature of the linkages based on current information is one of hypothesized causality. In that sense, SD modelling practice is consistent with a better delineation of causal factors that is often the research goal, even when this is more difficult to achieve. Moreover, the characterisation of different degrees of evidence about causal relationships in Habicht et al.[48] supports an emphasis on causality, but which can be evaluated through assessments of "adequacy", "plausibility" and "probability," depending on the degree to which the decision maker needs to be confident that any observed effects are due to a particular linkage, programme or intervention. This view encourages the inclusion of a wider range of information—as relevant to a specific linkage—and draws attention to the need for assessment of the strength of the inferences about the relationships of interest, which seems consistent with our recommendation above.

Box 1. Points involved in the development of causal diagrams

1) Variables should be specific and measurable (observable in principal) and named as nouns or noun phrases rather than verbs indicating directions of change;
2) Linkages shown are hypothesized to be causal, not only correlations or associations;
3) Polarities of the links should be indicated;
4) Feedback loops should be identified and their polarity indicated;
5) Stocks should be depicted with boxes, and the use of other shapes is limited for clarity;
6) Important known or hypothesized delays (where time is required for a change in a causal variable to have an impact on a resulting variable) should be indicated.

The diagram from Kadiyala et al. can be modified based on these principles to illustrate the potential usefulness of the SD approach (Figure 3). For the purposes of this exercise, we have retained many of the variables from Figure 1, although in principle additional modifications for greater specificity (point 1 above) and alignment with the evidence in the text may be appropriate.

Figure 3 about here

Figure 3. Diagram Modified from Kadiyala et al.[8] Using Systems Diagramming Conventions. Stocks are shown in boxes. Variables in red seemed implied by the Kadiyala et al diagram (disaggregation of child and maternal health and nutrient intakes, other non-food expenditures, and household-level food production) and were added to clarify the nature of the hypothesized pathways. Exogenous variables are indicated in orange and potential intervention points in pink. The signs '+' and '-' indicate that the direction of the change in a resulting variable is the same as, or opposite of, the direction of change in a causal variable, respectively. '?' indicates an ambiguous direction of change. Reinforcing processes are indicated by the R enclosed by a clockwise arrow. Dashed arrows represent hypothesized additional loops.

Consistent with the guidelines above, the diagram now indicates hypothesized or known linkages among elements of the pathways linking agriculture and nutritional outcomes. Some variable names have also been adjusted as per SD naming conventions. Known or hypothesized causal links between variables, along with their polarities, are indicated. The direction of the change in a resulting variable may be the same as that of the causal variable or the opposite. For example, an increase in household income is hypothesized to lead to an increase in food consumption expenditures, whereas a decrease in household income would lead to a decrease in food consumption expenditures (i.e. positive polarity). An increase in women's energy expenditure may cause a decrease in maternal health status and vice-versa (i.e. negative polarity). Note that these situations indicate the directions of change between causal and resulting variables and do not imply symmetry in the nature of the responses to increases and decreases.

It is not considered good SD diagramming practice to have linkages with ambiguous polarities. Typically, this implies a lack of specificity for variable names, as all variables should have clear hypothesized causality – and not just be general categories of variables. An example is the *Drivers of "taste"* variable included in the Kadiyala et al framework shown in Figure 1, which contains many sub-elements (culture, location, growth, globalization) that could influence *food expenditure*; and includes a variable such as *culture* that does not suggest a specific relationship with food expenditures. The polarities of these different embedded relationships are not separately accounted for in the original Kadiyala et al framework from Figure 1, so we have similarly shown these ambiguous polarities only to maintain consistency with the original diagram from Kadiyala et al. We emphasize that in SD diagramming practice *all* polarities must clearly indicated.

Selected feedback loops and their polarities are also identified and emphasized beyond the one feedback loop shown in Figure 1. In principle, all feedback loops and their polarities should be identified and the loops named, but for simplicity this is not done here. For example, the main feedback loop shown in Figure 3 (R1) links household assets to household income, and nutrient consumption to nutritional outcomes at the household and national levels, which ultimately affects household assets. Feedback loop polarity is defined as the resulting direction of change in a variable through the feedback process if that variable were to increase. For example, if household assets were arbitrarily increased, this would increase incomes, food expenditures, nutrient consumption, nutritional status (at the household and national levels) – *and also* household assets. Identifying reinforcing feedback loops has relevance because these loops can often serve as a focal point for interventions to promote sustained improvements[49].

A "balancing" loop is shown between food prices and food production. If there is an increase in food production, there will be a decrease in food prices, other things being equal; the link polarities (positive or negative) in feedback loops indicate partial effects, not overall directions of change. A decrease in food prices is hypothesized to decrease food production keeping other things constant (i.e. through a producer's supply response), so an initial increase in food production levels will eventually be at least partly offset by this supply response effect of future price decreases. Balancing loops often indicate processes that need to be overcome or weakened to promote sustained improvements in outcomes. Our representation suggests that the underlying system structure is more "feedback rich" than is shown in Figure 1.

A number of variables including household assets, health status and nutritional outcomes are considered stocks. Stocks can be observed or measured at a particular point in time. They can include physical quantities (of goods or money), physical states (such as health status) or even emotional states. One reason to clearly delineate stocks is that they are sources of "memory" and inertia in a system; they accumulate the effects of a variety of previous causal factors and are sources of delays in responses, which can be particularly important to assess the likely impacts of interventions. Delays are shown with the "//" symbol on some of the causal linkages, e.g. those relating improved nutritional status to increased nutrient intake. This reflects the fact that time is often required after nutrient intakes are increased to demonstrate substantive improvement in nutritional status. The indication of a delay depends on the time required for a causal impact to occur, relative to the time horizon defined for the conceptual framework. Consideration of delays is often relevant for effective intervention design, which can also be linked to appropriate timing and metrics for monitoring and evaluation.

Finally, a model boundary diagram (MBD) is a useful construct to provide additional perspective on the hypothesized relationships. It consists of a listing of the exogenous, endogenous and excluded (or only implied) factors represented in the framework (or diagram). The MBD provides one indicator of the degree of assumed endogeneity and also indicates which concepts have been excluded. This sort of construct is important for ensuring that relevant feedback processes are captured, as indicated by Bené et al.[1], but also for providing a checklist for discussion, as the analyst can relate the framework to the evidence to explain why certain processes were excluded.

The MBD applied to Kadiyala et al. indicates a number of important exogenous *drivers*, especially those related to policy (Table 5). Many factors are represented as endogenous with some feedback processes implied. However, the nature of the variables excluded from the diagram (which can include those that are implied but not explicitly represented) suggests that the diagram does not always align with the factors for which the empirical evidence is summarized in the text. In addition, the discussion often omits components of the causal pathways identified in Figure 3. For example, Kadiyala et al (p. 48) notes evidence that increases in household income will result in increased caloric intake. However, the linkages between income and caloric intake in Figure 3 are more complex than those discussed in the text; they include hypothesized pathways through food and non-food expenditures and nutrient consumption—besides other potential causal variables such as food prices and women's employment. Omitting evidence about some causal pathways is understandable given the nature of the studies reviewed but does not facilitate the use of the diagram to understand the discussed linkages and their polarities.

Table 5 about here

Adaptation of a framework using Systems Modelling Tools

Systems modelling tools and principles can be used to strengthen the presentation of conceptual frameworks, such as those considering the links between agriculture and food security. First, this approach can improve the understanding of causal linkages, both in isolation and in feedback processes, and then assist in identifying the type and nature of relevant interventions. Many existing diagrams summarizing linkages in conceptual frameworks have ambiguous meanings (particularly when arrows are drawn to arrows, such as when *intra-household inequality* is linked to an arrow connecting *nutrient consumption* to *nutrient intake* in Figure 1). Clarifying the polarities of individual linkages provides additional information that summarizes existing knowledge or identifies relevant testable hypotheses. Identification of major feedback loops is important because they are key components of system structure and, as such, influence observed behaviours. Changing outcomes thus relies on understanding (and in some cases modifying) feedback processes that limit the ability of the system to change—particularly balancing feedback processes. The SD approach encourages analysts to clearly identify outcomes to be changed (through a reference mode diagram like Figure 2) and delineate factors internal to the system (endogenous variables) so that they appropriately represent existing evidence and the potential impacts of proposed interventions.

Our diagram (Figure 3) indicates three potential types of interventions that might be undertaken to improve child nutritional outcomes (as one possible outcome, consistent with the reference mode shown in Figure 2). Along one of these pathways, a successful intervention to increase the productivity of crop and livestock production will increase food production, which, through an increase in quantity, would increase the value of food produced by the household (i.e. as imputed income). However, if increased production is sufficiently widespread, this has a decreasing effect on food prices, with a corresponding impact on the value of home food production. The net effect is an empirical question—one with great importance for determination of the appropriateness of using increased agricultural productivity to improve nutritional outcomes. Along another pathway, a successful intervention to improve public health access is hypothesized to improve child and maternal nutritional outcomes. This is hypothesized to then lead to increases in household assets, and thus higher income nutrient intakes and nutritional outcomes, but the delay shown in the diagram between *national nutritional outcomes* and additional household asset accumulation suggests that this process may take time to achieve, especially if variation in within household equity is considered. The nature of the delays and their causes are thus a relevant component of a research agenda to better understand which interventions matter most, their sequencing, and timing. It is a testable hypothesis whether there is an additional feedback loop (shown in Fig. 3 with dashed red arrow) connecting current income to household asset accumulation that would operate with stronger impact on a shorter time scale than effects through national nutritional status averages.

Finally, an intervention to empower women is shown as reducing intra-household inequality (a negative polarity for this linkage means that decreased inequality implies improved care), which is hypothesized to have a positive effect on the effectiveness of care and thus child health outcomes. However, intra-household inequality is shown as an exogenous variable—uninfluenced by other factors in the framework. Another testable hypothesis is whether endogenous factors (perhaps household assets) affect the degree of intra-household inequality; if so, interventions to empower women would be enhanced through feedback mechanisms.

Another advantage of the systems modelling tools discussed here is that there is a well-developed approach to derive frameworks with them using participatory methods[50]. Such an approach can facilitate shared understanding by stakeholders with alternative perspectives and greater consensus on what actions are appropriate. In some settings, the analysis of 'system archetypes'[51] and 'systems traps'[52] may provide additional insights about the appropriateness of intervention strategies. One system trap relevant to this framework is 'policy resistance', where intended improvements are undermined by so-called 'side effects'. This trap is illustrated by the discussion above of the ambiguous impacts of productivity increases: intended improvements in food security may be undermined by scaling-up market effects.

The specification of a reference mode, a causal system diagram, and a MBD are useful to enhance understanding of the linkages between agriculture and food security for the reasons noted above. However, diagrams alone (for any type of conceptual diagram) cannot quantify the direction and magnitude of changes over time in response to specific interventions. One example has been noted previously: the impact of (scaled-up) increased agricultural productivity on nutritional outcomes is an empirical question highlighted by the alternative pathways influencing household income (through quantities and prices). As Sterman[2] notes, "In systems with significant dynamic complexity, computer simulation will typically be needed" to assess intervention priorities more rigorously. SD diagramming tools are steps in a process to the development of quantitative simulation models that can provide additional insights about the linkages between agriculture and food security, as demonstrated in Nicholson et al.[53]

The SD approach has a clear overlap with concepts from Theory of Change (TOC) in that both focus on a long-term goal or outcome, consider what conditions must be in place to achieve this goal, and delineate causal pathways[54]. This conceptual overlap suggests that application of SD concepts could be complementary to TOC. TOC methods, however, are used mostly in project and programmatic contexts to delineate what needs to happen to have the project or program work more effectively. They seek to make explicit connections between inputs, activities, outputs, outcomes, and impacts, with a particular view to informing monitoring and evaluation.

Some parallels also exist between SD and Program Impact Pathways (PIPs), which are theory-based, schematic diagrams that display the conceptual pathways "from an intervention input through programmatic delivery, household and individual utilization to its desired impact"[55]. PIPs can be useful to elucidate how programs or interventions work (the mechanisms) and under what conditions (mediating or modifying determinants[56,57]). PIPs have been increasingly adapted from the field of evaluation and applied to small and large nutrition program development, monitoring and evaluation, and research. Earlier versions of PIPs were used to design program process evaluations post-hoc[58,59] , while more recently, PIPs are being used in the program development and design phase and used for monitoring and real-time adaptation to strengthen intervention delivery[60,61]. Although the use of PIPs allows nutrition interventions to be more grounded in theory, they have been designed and displayed in multiple formats, usually representing linear unidirectional relationships and with varying representation of mechanisms and interactions between inputs, behaviours, and outcomes. The use of PIPs to guide collection and analysis of data also lacks uniformity, ranging from simple comparisons between groups to structural equation modelling.

Undoubtedly, some readers will prefer the relative simplicity of Figure 1 to that of Figure 3, because the 'optics' of conceptual frameworks can be quite important for some audiences and purposes. However, we note that a main purpose in developing this diagram was to illustrate the potential usefulness of the approach, the result of which can differ from a diagram that would be most effective to communicate key messages about a particular system and potential interventions. Any SD-based diagram will be more effective when appropriately focused on variables associated with its purpose, and with consideration of the time scale and main feedback effects. However, even for more complex diagrams such as this one, visual representation can be done in a manner to make key messages more accessible to non-experts by including basic definitions of system concepts and sequential additions of relevant stock-flow and feedback structures. A diagram showing the system structure underlying the linkages between livestock ownership and nutritional outcomes in Randolph et al.[9] has been effectively presented to diverse audiences using this approach. In addition, the potential for development of systems diagrams using participatory stakeholder processes can facilitate shared understanding and appropriate application of an SD-based framework for decision making generally[50] and specifically for nutrition issues[62].

Conclusion

A main purpose of this paper is to highlight the usefulness of systems thinking and modelling conventions and tools for the assessment (and future development) of conceptual frameworks linking agriculture and food security, as well as to recommend the use of a checklist consistent with these concepts (Table 2). We specified a set of relevant evaluation criteria based on these conventions (which may in and of itself be useful) and used these criteria to assess a set of existing frameworks from the literature. That assessment suggests that conceptual framework development and application would be improved with a greater focus on specific dynamic behaviour(s) over relevant time horizons and explicit consideration of the nature of stock-flow-feedback processes—and decision rules used by actors—that generate them. Clearer definition of system boundaries (i.e. what is endogenous, exogenous and excluded) would complement the development of frameworks with these characteristics. Because frameworks are likely to be more useful when they can shed light on the likely impacts of various interventions on specific outcomes, improved delineation of intervention points and discussion of the likely directions of impacts can add value to existing frameworks and facilitate subsequent quantitative analysis of relevant hypotheses.

Conceptual frameworks matter because they capture a worldview—how we perceive different elements as interacting to affect outcomes—and thus influence how resources are allocated for programmatic and research efforts. On the basis of our review, the predominant worldview emphasizes static analyses in which individual variables can be modified to achieve outcomes with limited consideration of the impacts of other interactions (balancing feedback loops) or potentially-important time delays. This view aligns with the development of shorter-term projects working to research or intervene on discrete or disconnected elements of a system to achieve change. In contrast, the SD-based approach recommended above explicitly recognizes dynamics and system linkages, which in many cases aligns more closely with the realities of the complex and dynamic systems that must be modified to improve food security outcomes. SD emphasizes the need for the perspectives of multiple disciplines to understand and act upon these linkages. A more dynamic approach like SD provides both a tool for initial assessment of interventions (e.g., pathways and testable hypothesis) but also facilitates assessment of the sequencing of the interventions that is more likely to bring about lasting change. SD also implies that not all pathways matter equally and that facilitating positive outcomes through some pathways may require heavy investments for long periods.

Systems thinking and SD modelling have a long history of applications in diverse fields—but have been less used in the analysis of food and agricultural issues. It appears that they would have great potential to contribute to improved thinking about the complex linkages between agriculture and food security, particularly given the increased focus on developing sustainable food systems that provide healthy diets and operate within planetary boundaries.

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Contributions

All authors contributed to the development of the structure of the article and the criteria for assessment. Nicholson, Kopainsky, Stephens wrote the first draft, with subsequent input from other authors. Kopainsky and Stephens developed the summary in Table 3, and Nicholson developed the application of systems modeling tools to the Kadiyala et al framework.

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Ethics declaration

Competing interests

The authors declare no competing interests.

Table 1. Potential Purposes for Conceptual Frameworks Linking Agriculture and Food Security Used for Assessment

Purpose of the Framework	Description
Exposition	Accompanies a text description of concepts and linkages to facilitate reader understanding
Evidence summary	Provides a summary of empirical evidence about specific linkages or pathways
Logical rigor	Facilitates a conceptual analysis of key components underlying food security outcomes, often for research or policy design
Empirical model components or computations	Depicts specific model components or computational procedures for empirical models
Framing of testable hypotheses	Depicts pathways with the purpose of identifying hypotheses testable with further research or policy experiments

Table 2. Assessment Criteria for Conceptual Frameworks Linking Agriculture and Food Security, Emphasising Concepts from Systems Modelling

Assessment Criterion	Description
Framework purpose	*The intended purposes of the framework are clearly stated.* Purposes could include exposition, evidence summary, or enhancement of logical rigor in analysis of system interactions.
Model boundary	*The framework clearly indicates what components are endogenous (determined by internal interactions among elements of the framework), exogenous (influences not determined within the framework) and excluded (not represented).*
Linkage polarity	*The 'polarities' of hypothesized linkages are clearly indicated.* Polarities indicate whether the directions of change are the same or opposite for changes in one variable hypothesized to cause changes in another.
Feedback processes	*Feedback processes are shown explicitly when appropriate*, rather than only uni-directional or static linkages.
Dynamics	*Intertemporal dynamics are explicitly represented with a focus on explaining a specific behaviour over a relevant time horizon.*
Actors and decisions	*The actors, decisions and information used for decisions are clearly depicted.* Actors can include individuals (or households) acting as producers or consumers, private businesses, NGOs or government agencies, among others.
Levels of aggregation	*The levels of aggregation assumed (e.g. global, national, regional, local, household, intra-household) are included or emphasized when appropriate.*
Intervention entry points	*Potential intervention points are clearly indicated in the framework.*
Food security indicators	*Specific food security metrics representing relevant dimensions of food security (availability, access, utilization and stability) are included.*

Table 3. Summary Assessment of N=37 Conceptual Frameworks Linking Agriculture and Food Security

Summary Characteristic	Number of Papers
Likely Purpose	
Exposition	27
Evidence summary	13
Logical rigor	8
Other	4
Levels of Analysis Included (or Focus)	
Aggregated (general)	17
National	8
Household	12
Individual	8
Other (regional/flexible/unclear)	6
Actors (Decision makers) specifically defined	15
Dynamic dimension (stability outcomes) clearly indicated	8
Feedback processes indicated[a]	20
Intervention points specifically indicated (rather than implied)	7
Type of food security indicators included:	
General (e.g. "Food Security", "Malnutrition")	9
Availability	5
Access	8
Utilization	6
Stability	3
Nutritional status	14
Health outcomes	8
Consumption or intake	6
Other (dietary diversity, quality)	3
Not defined	5

Note: sums can add up to more than the total number of reviewed frameworks as one framework can, for example, have several purposes or be relevant at several levels.

[a] Includes all frameworks with potential or implied feedback processes, not just those frameworks with more substantive treatment and discussion of feedback processes and impacts, which are far fewer (N=7).

Table 4. Assessment Criteria for Conceptual Frameworks Linking Agriculture and Food Security, Applied to Kadiyala et al.

Assessment Criterion	Description
Purpose	Clearly stated, primarily a summary of empirical evidence: "In light of…complex linkages between agriculture and nutrition, the goal of this review is to systematically assess the available evidence in the Indian context."
Model boundary	Could be more explicitly described as such, but *policy drivers* (of growth, inequality and nutrition) appear to be exogenous, affecting household assets, resource access, tastes, intra-household inequality and public health. Excluded variables not explicitly discussed. Endogenous factors shown but not clearly described as such.
Linkage polarity	Polarities not indicated in the diagram. Some linkages likely have ambiguous polarities. For example, food prices (represented with a single arrow) can increase or decrease food expenditures depending on food demand elasticity values.
Feedback processes	A limited number of feedback processes are shown (e.g. linkages between household assets and nutritional status). Neither feedback loops nor their polarities are emphasized.
Dynamics	No explicit behaviour over time is highlighted, and language focused on *pathways* suggests a more linear conceptualization. Time horizon for impacts not clearly defined, although data show outcomes.
Actors and decisions	Actors implied include households, women, policy makers (governments). Specific decisions not emphasized.
Levels of aggregation	Specifies national level (for food markets), household level (for income generation and expenditure) and Individual level for nutrient intake and health status.
Intervention entry points	Implied by exogenous policy drivers for government, but no specific interventions are associated with policy or indicated elsewhere in diagram.
Food security indicators	Multiple indicators include *food output* (availability), *food expenditures* (access), *nutrient intake* and *nutrition outcomes* (utilization). No explicit mention of the stability component of food security.

Table 5. Model Boundary Diagram Based on the Conceptual Diagram in Kadiyala et al.

Exogenous Variables	Endogenous Variables	Excluded[a]
Policy drivers of inter-household and intra-household inequality	Food production, imports, and prices	Agricultural productivity
Policy drivers of nutrition	Non-food production	Household-level food production
Policy drivers of (economic) growth	Household income and employment	Specific indicators such as stunting
Water and sanitation quality	Household expenditures on food, non-food and health care	Crop diversification
Health services	Women’s time allocation to employment	Dietary diversification
Education access and quality	Household nutrient consumption	Livelihood diversification
Access to credit and public services	Caring capacity and practices	Livestock assets (although part of household assets)
Tastes and preferences (and their drivers)	Women’s and children’s health status	Animal-source foods (although part of nutrient consumption)
Gender bias	Women’s energy expenditure	Household net producer status
Family size	Nutrient intake	Relative prices of micronutrient -rich foods
	Child and maternal nutrition outcomes	Women’s asset ownership
	National nutrition outcomes	
	Household assets (livelihood strategies)	

Note: Columns provide a listing of the three types of variables included in a typical Model Boundary Diagram. There is no linkage among these concepts across the rows of the table.

Note: Exogenous variables are those assumed given for the purposes of the conceptual framework (diagram), i.e. those not changed by other elements of the framework. Endogenous variables are those affected by other variables shown in the framework. Excluded variables are those not explicitly shown in the diagram that could affect outcomes of interest.

[a] In principle, the list of “excluded” variables can be quite large, but the focus here is on those that might reasonably be linked to included variables but are not given the focus provided by the reference mode behaviour. Note that the excluded variables in model boundary diagrams can also serve as a basis for critiquing the framework by highlighting omitted variables. We provide only a few examples here based primarily on concepts mentioned in the text but absent from Fig. 1.