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Participatory systems modeling of food value chains to improve food and nutrition security under climate change

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The threats posed by climate change to food and nutrition security are growing, and the need to develop actions to both mitigate and adapt to climate change is increasingly important. A systems approach to governance that involves stakeholders at the scale of food value chains can address important knowledge gaps between climate change and food and nutrition security outcomes, and facilitate identification and implementation of high-leverage *ex ante* mitigation actions. Participatory Systems Modeling (PSM) is a methodological approach to identify and assess priority actions that combines facilitated stakeholder discussions with the development of quantitative inter-temporal systems simulation models. PSM has potential benefits deriving from the involvement of stakeholders, the application of well-developed quantitative systems modeling methods, flexibility, low cost and linkages to other systems-oriented frameworks. We propose a roadmap for scaling PSM through multi-context case studies and further development of standardized best practices.

KEYWORDS
climate change, food and nutrition security, group model building (GMB), participatory system dynamics (PSM), system dynamics (SD)

1 Introduction

Climate change poses a growing threat to Food and Nutrition Security (FNS), especially in lowincome countries (Fanzo et al., 2017). The pathways linking climate change to FNS are complex and dynamic (Bizikova et al., 2020; Nicholson et al., 2020; Fanzo et al., 2021). FNS outcomes are multi-dimensional, including food availability, access, utilization and stability (Nicholson et al., 2021b). Climate change has the potential to affect each of these through impacts on food production, food costs, dietary diversity, nutritional content and food safety. Substantive gaps exist in our understanding of potential negative impacts of climate change on FNS outcomes and assessment of interventions with potential to mitigate them, especially at the scale of value chains (Nicholson et al., 2021a; Slater et al., 2022).

Food systems require intentional governance[1] to achieve the transformations needed to address climate change and mitigate negative impacts on FNS (Mason-D'Croz et al., 2025). Effective governance "requires multiple food systems actors—across levels of government, sectors, and communities—are heard and participate as change agents" (Trevenen-Jones et al., 2025). A systems approach to governance that involves stakeholders at the scale of food value chains can address important knowledge gaps between climate change and food and nutrition security outcomes, and facilitate identification and implementation of high-leverage *ex ante* mitigation actions. This is because systems approaches can (a) consider interconnected and heterogeneous components of food systems across scales, (b) account for multiple complex interactions over time, (c) integrate existing knowledge, (d) identify priority actions, and (e) facilitate improved food system governance (Sterman, 2000; Institute of Medicine/National Research Council, 2015; Stephens et al., 2026).

The challenge of achieving enduring transformations in complex systems is that we are dealing with wicked problems, i.e., where the desired solution is hard to define and confirm once achieved, and the solution itself is multi-objective. Efforts to improve one objective can worsen other outcomes (Head and Alford, 2015). This creates the challenges of N-lemma policies, in which decision-makers must make hard choices and trade-offs. Systems approaches are critical for identifying these hard choices, making them more explicit, and informing decision-makers about the costs and benefits of interventions across the food system. Particularly when undertaken in a participatory manner, systems approaches can increase participants' understanding, thus strengthening their capacity and agency for change.

The objective of this paper is to describe the Participatory Systems Modeling (PSM) approach and discuss why applying it to the governance of food value chains can yield new insights into how to mitigate the effects of climate change on FNS. PSM is a systems-methodological approach for identifying and assessing priority actions, applying a variety of methods that combine system conceptualization and quantitative modeling (Sterman, 2006; Stephens et al., 2026). Although PSM has been developed over the past three decades, many analysts and practitioners may not be familiar with this approach. PSM is particularly well-suited to the inclusion of institutions and governance mechanisms in food systems. The PSM process is designed to integrate the principal factors affecting an outcome like FNS—it is interdisciplinary by nature—including biological, economic, social, and institutional interactions. Integrating these factors can improve understanding of the underlying causes of problematic food system behaviors and to identify feasible, high-leverage interventions to improve outcomes.

A key component of the PSM is the involvement of stakeholders in developing both conceptual and quantitative models of the system to explain specific important outcomes. Stakeholder involvement is a common element of many participatory approaches applied to food systems, such as Participatory Rural Appraisal (Horstink et al., 2023), and others, such as Theory of Change (e.g., Loring et al., 2024), and Participatory Impact Pathway Analysis (Douthwaite et al., 2008) also describe potential impact pathways. However, PSM emphasizes the development of both conceptual and quantitative models that highlight stock-flow-feedback processes and intertemporal dynamics, and explicitly draws on relevant systems-analytical knowledge (e.g., Sterman, 2000) to address system complexity. The involvement of stakeholders in PSM enhances collective learning about the systemic origins of undesirable situations, builds consensus about appropriate actions (e.g., through evidence about which interventions are likely to have the largest positive impacts) to achieve desired outcomes, and provides motivation to undertake those actions. Food value chains are context-specific, with widely varied geographies and ecological, economic, and social conditions, so stakeholders' subject-matter knowledge can make important contributions to analytical methods and the identification of potential interventions. Participatory methods involving stakeholders can facilitate a more holistic understanding of food systems by drawing on both quantitative and qualitative information about how and for whom food systems work.

Although PSM can yield benefits at multiple scales, we highlight its use in analyzing food value chains. One motivation for this focal point is that value chains are now recognized as a key determinant of FNS, with developed conceptual frameworks (e.g., Fanzo et al., 2017) and efforts to implement "nutrition-sensitive value chains" (de la Peña and Garrett, 2018). A value chain perspective includes food processing (value-added) activities essential to assessing changes in livelihoods for people working in food systems, given that about 70% of value addition occurs after farm-gate (Yi et al., 2021). The impacts of climate change on food utilization, loss and waste will be determined by the decisions of value-chain actors and the dissemination of sociotechnical innovation bundles (Barrett et al., 2020). As a result, most interventions designed to improve FNS either necessitate or are facilitated by changes to the structure or capacity of food value chains (König et al., 2017). This applies whether the intervention is focused on food production (e.g., "nutrition-sensitive agriculture"), food consumption (e.g., social protection programs, income transfers, efforts for behavioral change) or reduced food loss or enhanced nutritional value through processing (Michel et al., 2024). Despite the potential importance of food value chains for implementing interventions, there is relatively limited work at this scale compared to either global-scale analyses or research on production-specific impacts (Moallemi et al., 2025a; Wiebe et al., 2025), and much previous work relies on indirect inferences about FNS outcomes (Mbow et al., 2019). In addition, value chains can be viewed as complex systems with multiple actors and interconnections, whose analysis is facilitated by systems-analytical approaches. PSM can be applied most readily at local and regional scales for reasons described below, which often aligns with the scale and structure of food value chains. Recent literature (e.g., Bexell et al., 2025) has highlighted the importance of subnational and local efforts in implementing the Sustainable Development Goals (SDGs), including SDG 2, Zero Hunger.

The first section of the paper provides examples of the types of methods used to assess the linkages between climate change and FNS outcomes, although it is not intended to be a systematic review of this literature. We then describe the elements and process for PSM, providing a detailed example of its application. Given that multiple systems-analytical methods exist, we next summarize the key lessons from applying PSM more generally and to the food system governance, and

1 Food governance can be defined as "the structures, processes, and decision-making mechanisms shaping food production, distribution, and consumption. It involves state, market, and civil society actors, alongside norms and regulations" (Sustainability Directory, 2024).

discuss the admittedly somewhat incomplete evidence on its impacts when applied to FNS outcomes. The final section summarizes other aspects of PSM for analyzing value chains and suggests next steps for a more rigorous evaluation of PSM as a method for identifying effective interventions in food value chains in the context of climate change. Although our focus is on contexts in Low- and Middle-Income Countries (LMIC), much of the initial discussion is general, with subsequent focus on LMIC in the discussion of proposed next steps for PSM implementation.

2 Previous approaches to analysis of climate change and food security

To place the applicability of PSM in an appropriate context, it is useful to discuss the methods applied in previous work assessing the linkages between climate change and FNS outcomes. There is a large and growing body of literature on this topic. A Scopus search of the terms "climate change" AND "food security" OR "nutrition" returned 42,764 records. A subsequent narrowing to "climate change" AND "food security" AND "impact" yielded 3,704 records. A preliminary assessment of the 3,704 documents was undertaken for this paper. Many of these studies mention food security as a motivating factor for discussing climate change, but do not analyze the linkages between the two topics, either conceptually or empirically. Previous studies summarized below comprise conceptual frameworks, ex post statistical analyses of climate impacts, simulation studies of adaptation strategies in food value chains, and simulation studies of long-term future impacts.

2.1 Conceptual frameworks linking climate change and FNS

Numerous conceptual frameworks describe the hypothesized linkages between climate change and food security (e.g., Tirado et al., 2009; Myers et al., 2017; Fanzo et al., 2017). The conceptual diagram from Myers et al. (2017) provides more detail than most frameworks about impact pathways (Figure 1). This diagram includes multiple pathways of impact on crops, livestock, fisheries and enteric disease, and incorporates biophysical, economic (both micro- and macro-economic), social and political impacts. Similar to many conceptual diagrams evaluated by Nicholson et al. (2020), the Myers et al. diagram (a) is essentially linear (no feedback processes are shown or dynamics implied), (b) does not clearly delineate the different dimensions and metrics of FNS (e.g., "altered nutritional status" is the end outcome) and (c) lacks specificity in the diagrammatic conventions (e.g., about the likely directions of impact). In addition, this and most

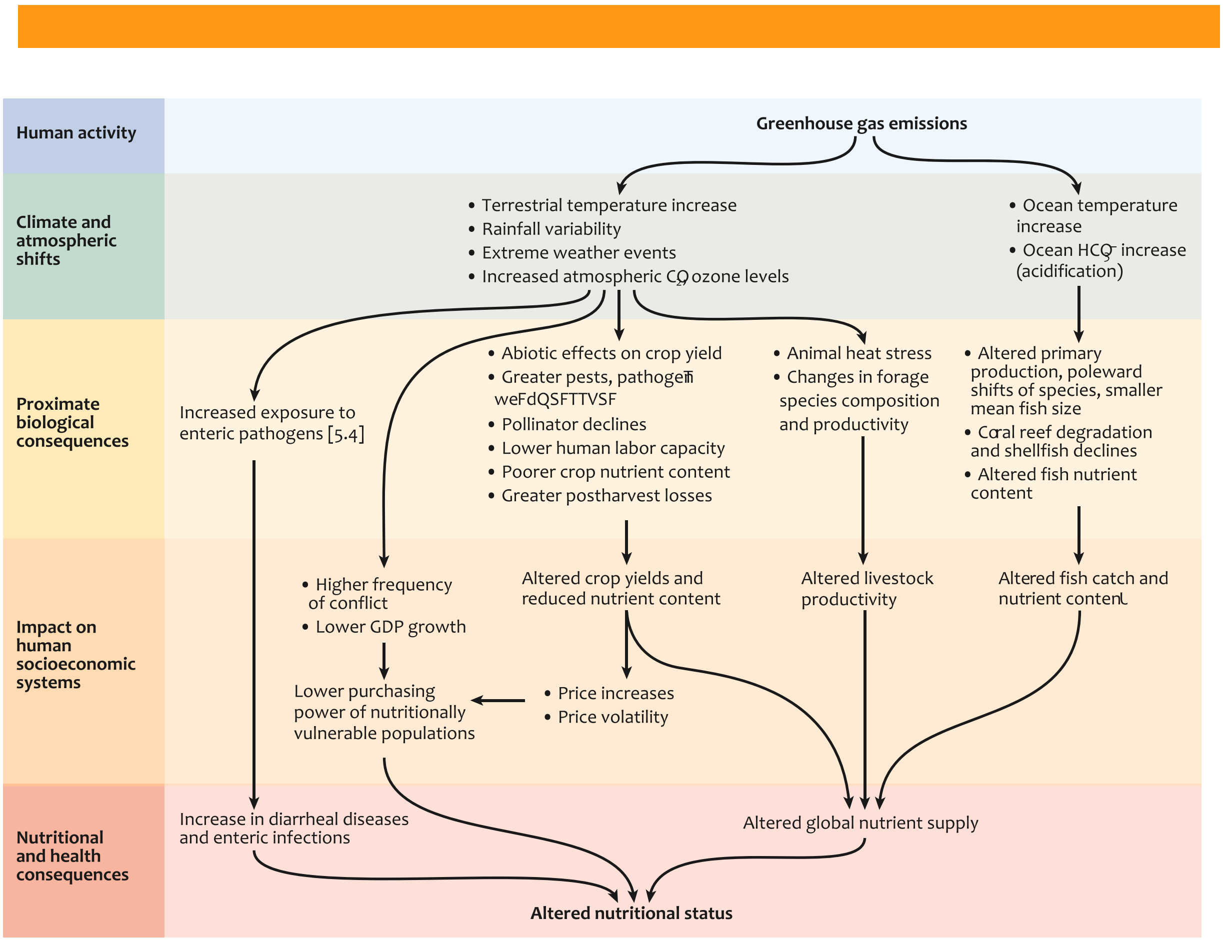

FIGURE 1
Potential pathways for impact of climate on undernutrition (source: Myers et al., 2017). Reprinted with permission from Climate change and global food systems: potential Impacts on food security and undernutrition by Myers et al. (2017) Copyright (c) 2017 Annual Reviews.

conceptual diagrams omit potential intervention points and their intended pathways of impact. Many diagrams focus on biophysical outcomes without recognizing their linkages with social, economic and political processes.

Fanzo et al. (2017) developed a conceptual diagram (Figure 2) to address another potential limitation of many of the conceptual models linking climate change and FNS: most components of the food value chain are omitted or highly aggregated. Using an explicit "value chain" approach, this diagram highlights factors that could reduce "nutritional value" at multiple stages and suggests potential interventions to maintain that value through to consumption and utilization. This diagram describes a linear flow process beginning with input supply and ending with consumption—again implying limited consideration of feedback processes or dynamics. It highlights the impacts of multiple post-farm and processing activities on nutrition, which have received less attention in the literature linking climate change to FNS. Although not clearly linked to climate change, this diagram provides a useful complement to others because it recognizes that many other activities (and actors) are involved in the production and distribution of food, and implicitly that growing populations in LMIC are not food producers or 160 are net buyers of food rather than subsistence producers (Stephens and Barrett, 2011).

2.2 Ex-post statistical studies of climate impact on FNS

The most common empirical studies on the linkages between specific climate variables (or climate variability) and FNS outcomes use statistical rather than systems-modeling methods.

For example, World Health Organization (WHO) (2019) provided a summary of the likely effects of "environmental change" on key risk factors for undernutrition based on prior studies and hypothesized impact pathways. Many previous studies have identified associations between climate-related variables and FNS metrics across various temporal and spatial scales (e.g., Cooper et al., 2019; Belesova et al., 2019; Bahru et al., 2019) and have emphasized child nutritional outcomes such as stunting or wasting. These studies often find a statistically significant impact, but lack a clear description of the broader significance for human health. In addition, Belesova et al. (2019) noted that attributing causality from these analyses can be challenging, for example, that the extent to which child undernutrition is attributable to drought "has not been clearly quantified and may be context-specific." Although these statistical studies provide useful quantitative evidence on the linkages between climate change and FNS, many are limited by the degree to which causality is clear from the data and methods, the extent to which causal pathways are understood, and their usefulness for identifying intervention priorities.

2.3 Simulation modeling of climate impacts and adaptation interventions in food value chains

A relatively small number of studies have addressed the impacts of climate and proposed interventions at the scale of a food value chain. Wossen and Berger (2015) evaluated the impacts of climate variability in northern Ghana using an optimizing agent-based model of a population of farm households. They found that climate variability reduced the mean farm household income and lowered its variation, but did not much affect the proportion of households below a poverty line. The FNS indicator was food energy consumption, for which the impacts of climate variability were not evident. The study analyzed the impacts of interventions to improve farm credit access and off-farm employment to address climate variability, suggesting that these interventions improved farm income, but they did not report impacts on food energy consumption. Bakker et al. (2018) used a spatially-disaggregated but stylized agent-based model for Ethiopia to assess the impacts of five potential interventions on caloric intake in response to a 25% crop yield reduction in one production region. They found that cash aid and food aid mitigated the impacts of the production shock better than subsidies to producers or consumers or further development of regional transportation infrastructure.

Although these studies provide useful information, they did not include stakeholder participation.

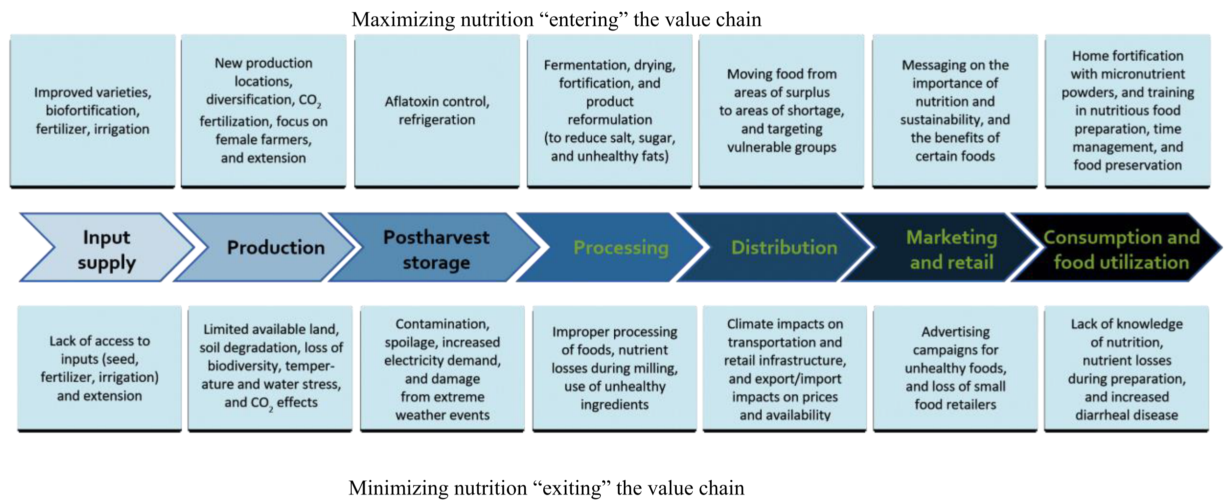

FIGURE 2
Value chain conceptualization of nutrition (source: Fanzo et al., 2017). Reproduced with permission from the International Food Policy Research Institute (IFPRI), https://www.ifpri.org. The original text is available online at https://hdl.handle.net/01568/146480.

2.4 Long-term projections of future climate change impacts on FNS

A growing number of studies have considered the long-term impacts of climate change on various food security metrics using simulation models, often with a focus on food production at global or national scales. One of the earlier studies is Parry et al. (2005), which used a computable general equilibrium (CGE) model to assess the impacts of climate on cereal crop yields and "people at risk from hunger." Nelson et al. (2018) projected macronutrient and micronutrient availability in 2050 with country-specific biophysical and socio-economic scenarios. They found that the positive effects of income growth on availability offset the negative climate effects. Hasegawa et al. (2018) employed a multi-model analysis indicating that both climate change *per se* and efforts to mitigate greenhouse gas emissions could have negative effects on dietary energy availability in 2050. Islam et al. (2016) discuss an approach that "integrates biophysical modeling with economic modeling to explore the combined effects of climate stresses and future socioeconomic trends." Their analysis integrates common crop simulation models with the global partial equilibrium IMPACT economic model to assess the impacts in 2050 on the yield of selected crops and their related prices. They appropriately note a limitation of their study:

> It is recognized that food security is a multi-dimensional issue, including (1) food availability, (2) access to food, (3) stability and (4) food utilization (FAO, 2008). However, most simulation studies only capture one aspect of insecurity when looking at climate change impacts, i.e., availability…This is also a limitation in our study.

This basic approach of integrating biophysical and economic models can also be used to assess the impact of investments on agricultural productivity in light of climate change. Mason-D'Croz et al. (2019) evaluated the combined effects of climate change and productivity gains on incomes, commodity prices and food demand, with the per capita caloric availability the primary reported indicator related to FNS. The study concluded that "Investments to increase agricultural productivity can offset the adverse impacts of climate change and help reduce the share of people at risk of hunger in 2030 to 5 % or less in Northern, Western, and Southern Africa, but the share is projected to remain at 10 % or more in Eastern and Central Africa."

2.5 Summary of studies on climate change and FNS

Prior work on climate change and FNS provides relevant information on the potential impacts on long-term, geographically aggregated food security metrics at the population level (e.g., using mean caloric availability). Previous approaches have strengths due to their conceptualization of FNS determinants and the use of rigorous statistical analyses or quantitative simulation analyses and can be applied at scales ranging from local to global (Table 1). Regional or global-scale analyses assess the impacts of selected general policy approaches, such as climate mitigation or investments in agricultural productivity. Despite these strengths, both the conceptual and quantitative analyses in prior work often appear limited by (a) lack of context specificity for impacts or interventions, (b) omission of post-farm supply chains, (c) inability to assess path dynamics that could imply worse-before-better (or better before-worse) behaviors (Jagustović et al., 2021; Moallemi et al., 2025b), (d) limited consideration of relevant FNS metrics for access and stability, not just availability, and (e) greater difficulty in involving stakeholders in their development or

TABLE 1 Comparison of alternative approaches to analysis of FNS outcomes under climate change.

Method	Strengths	Limitations	How PSM addresses limitations
Conceptual frameworks linking climate change and FNS	Maps linkages between climate and FNS to guide future work and interventions. Low cost of development.	Existing frameworks tend to focus on biological responses and have limited feedback. Impacts of interventions cannot be reliably inferred from conceptual diagrams. Limited stakeholder engagement and ownership, often not context-specific.	The GMB component of PSM engages stakeholders to develop broader conceptual diagrams with feedback, then complements that with quantitative systems modeling of specific interventions.
Ex-post statistical studies of climate impact on FNS	Statistical rigor in methods, well known to most researchers and therefore scalable.	Requires extensive data, statistical significance may not suggest broader impacts for human health, often limited ability to infer causal mechanisms and which interventions would be most beneficial. Limited knowledge from stakeholders.	Engages stakeholders to develop relevant data useful for modeling, then complements that with quantitative systems modeling of specific interventions.
Simulation modeling of climate impacts and adaptation strategies in food value chains	Rigor in quantitative methods, ability to analyze multiple scenarios and assess interventions at various scales.	May face data challenges or lack representation of key system elements given limited stakeholder engagement in model development. Often will not facilitate learning and consensus for action.	Involvement of stakeholders promotes ownership, learning and consensus building and may identify system structure or data to support improved quantitative analysis.
Long-term projections of future climate change impacts on FNS	Rigor in quantitative methods, ability to analyze multiple scenarios to document the scope of future FNS challenges.	May face data challenges or lack representation of key system elements given limited stakeholder engagement in model development. Most analyses are global in scale, limiting context specific inferences about impacts and appropriate interventions.	Involvement of stakeholders promotes ownership, learning and consensus building and may identify system structure or data to support improved quantitative analysis. Better conceptual fit with analysis at the scale of value-chains.

application[2]. Prior studies have, in general, also provided limited guidance on investment or intervention priorities, e.g., through comparative studies of interventions and impacts on relevant sub-populations. As we discuss below, PSM has the potential to address each of these limitations when applied to a specific food value chain context, given its ability to assess complex system dynamics, incorporate metrics other than food availability (e.g., Nicholson et al., 2021b), and engage stakeholders in the identification and assessment of context-specific interventions.

3 Participatory systems modeling

PSM combines participatory system conceptualization with quantitative modeling. Systems are often defined as having three components: elements, interconnections, and a function or purpose (Meadows, 2008), which are sometimes referred to collectively as *system structure*. Food systems are often described as "complex adaptive systems" (Institute of Medicine/National Research Council, 2015), characterized by heterogeneous individual actors, feedback processes, and nonlinear and dynamically complex behavior. As a result, they often exhibit path dependency and counterintuitive responses to proposed interventions, so systems-analytical approaches that account for these characteristics can inform interventions to improve food system governance. Both conceptual and quantitative systems analytical approaches are relevant. Conceptual modeling of a system typically includes mapping the elements and their interconnections using methods such as Group Model Building (GMB; Vennix, 1996), soft systems methodology, and fuzzy cognitive mapping. These maps provide the conceptual basis for quantitative models, including system dynamics modeling (SDM), agent-based modeling (ABM), and related role-playing games. A key component of the PSM is the involvement of stakeholders in identifying both conceptually and quantitatively the system structure that determines a specific outcome of importance, and in identifying potential interventions to improve that outcome. We focus on the combination of GMB and SDM because this approach has a long history of implementation and evaluation.

3.1 Group model building

GMB is generally conducted with a group of between six and 15 people from relevant stakeholder groups (Rouwette and Vennix, 2020) who share an interest in identifying effective actions to improve a specific outcome. A stakeholder is often defined as "an individual or group that has an interest in any decision or activity of an organization" (International Organization for Standardization, 2023), but this definition could be extended to multiple organizations when value chains are of interest. The relevant stakeholders will be context-specific, but GMB should attempt to include as many stakeholders as feasible, given limits on the overall size of the group. For PSM based on value chains, ideal GMB participants should represent each of the key decision makers in the value chain, including those with heterogeneous identities and lived experiences that may provide a relevant perspective or make them subject to differential impacts of proposed interventions (e.g., gender, age or ethnic identity; Mulema et al., 2022; Stephens et al., 2026). Because PSM seeks to influence both understanding and motivation to act, it is usually desirable for participants to have some decision-making power within the value chain. Stakeholders with relevant domain knowledge and without inflexible ideas about appropriate interventions are preferred participants in GMB. However, their selection must acknowledge the challenges of achieving appropriate inclusivity and facilitate the process in ways that acknowledge power dynamics (Hovmand, 2014).

GMB often starts by identifying the issue of interest, usually depicted in the form of a *reference mode of behavior*, a graph of the behavior of the most important variable (outcome) over a relevant past (or future) time horizon. Often, this behavior is considered "problematic" and a goal of PSM is to identify interventions to improve the behavior (Sterman, 2000). This *reference mode* provides a focus throughout the GMB process. It summarizes the level of abstraction chosen for the model, the time period the group is interested in, and the most important behavior to be simulated in a quantitative model. The next step in the process is the development of a conceptual model based on hypothesized causal relationships that generate the reference mode behavior and potential intervention points. This conceptual model integrates these causal relationships with feedback processes, and is often referred to as a "causal loop diagram" (CLD). The CLD serves as a basis for further quantitative model development using SDM.

3.2 System dynamics modeling

SDM is essentially the application of systems engineering concepts to social and economic systems and results in feedback-rich quantitative models that also capture relevant stock-flow dynamics. System Dynamics (SD) models are typically formulated as systems of ordinary differential equations that, because of their complexity (and sometimes nonlinearity), are typically solved by numerical integration rather than by analytical methods. The methods used in SDM overlap with other systems modeling approaches, but SDM also involves a particular *perspective* on the modeling process and interpretation of modeling outputs. This perspective involves a focus on dynamic complexity (when outcomes in response to interventions can differ in the short and longer-run), an endogenous perspective (system behavior arises from the structure of the system itself, not primarily due to external drivers), emphasis on feedback processes and explicit characterization of stocks and flows. The SDM component of PSM typically involves three steps (adapted from Sterman, 2000):

(1) *Formulation of a simulation model*. This includes (a) specification of structure and decision rules; (b) estimation of parameters, behavioral relationships, and initial conditions, and (c) tests for consistency with the purpose and model boundary (what is included, excluded or exogenous).
(2) *Model evaluation*. Multiple qualitative and quantitative evaluation methods exist for SD models (Sterman, 2000, describes 12 sets of model evaluation tests), but a typical approach would begin with comparing model-generated behavior with the reference mode specified by the stakeholders. Key questions include whether the model reproduces the identified problem behavior and the degree to which simulated behaviors are sensitive to changes in parameters or initial conditions.

2 Stakeholders have been involved in the application of global economic models to multiple country or subnational scales through "stakeholder generated narratives" and scenario development linked to Shared Socioeconomic Pathways (SSP) as in Palazzo et al. (2017). This has some similarities with PSM, but the focus is on scenario development rather than model development, and regional is a typical analytical focus.

(3) *Policy design and evaluation*. This is the ultimate goal of the modeling exercise, and includes (a) scenario specification to consider what conditions affecting outcomes might occur, (b) policy design to explore new decision rules and strategies that might be tried in the real world, (c) "What if" analyses to explore the effects of the possible policies, (d) sensitivity analyses to examine how robust the policy recommendations are under different scenarios and given uncertainties, and (e) evaluation of policy interactions to determine if synergies exist or actors engage in compensatory responses.

The GMB component often focuses on identifying a problematic behavior and developing a conceptual model hypothesized to explain its origins, and the SDM component on quantitative model development, testing, and application. However, it is not uncommon to include stakeholders in a review of the quantitative model and its parameters, and the use of the model for design and evaluation of interventions.

Antunes et al. (2015) synthesized characteristics of PSM that make it appropriate for consideration of food system governance:

> PSM goes beyond eliciting knowledge from stakeholders; it involves negotiating "shared ownership" of what outcomes are problematic, how system interactions result in those outcomes, and a shared understanding of the tradeoffs among different potential interventions.

3.3 Case example of PSM application

An ideal case example for our purposes would focus on how PSM was applied to a specific value chain to identify interventions to improve FNS in response to climate change impacts. Unfortunately, we are not aware of any PSM application with all of these attributes, which provides one motivation for developing a roadmap for exactly this type of work. Thus, to illustrate the steps in applying PSM, we focus on one study of the poultry value chain in Nigeria (Olabisi et al., 2021) that incorporates some discussion of climate change impacts, but no direct discussion of FNS outcomes. We consider each step of the PSM process noted above, although details are limited for some steps. The study was motivated by the importance of Nigeria's poultry sector and by the omission of the specific challenges faced by poultry producers from national climate change adaptation plans. They implemented a PSM process to improve understanding of how a changing climate would affect stakeholders in the poultry value chain and to generate insights for national policymakers.

Stakeholder selection and workshop structure. The PSM process included stakeholder workshops in three locations, two for the GMB component (October 2017 and January 2018; each with 37 participants) and one to discuss the quantitative simulation model and its results (June 2018). Participants included researchers working on climate change and agriculture, policymakers (e.g., director of government livestock services), poultry farmers, maize farmers (maize is a principal feedstuff), veterinarians, other input suppliers, and small- and large-scale food retailers.

Definition of the reference mode behavior. Stakeholders determined that the behavior of interest was the growth in national poultry production through 2060, accounting for potential impacts of climate change.

Causal loop diagram development. The participants developed a CLD depicting the key determinants of poultry production (including biological, economic, and policy variables) and their feedback structure. The process also identified potential negative impacts of climate change (e.g., increased mortality from extreme heat events) and possible mitigation actions (e.g., practices to reduce heat stress).

Formulation of the simulation model. A quantitative system dynamics model incorporating core concepts from the CLD was developed by the researchers and reviewed by a subset of stakeholders at the third workshop in June 2018. Olabisi et al. do not provide substantive detail on the specific decision rules, parameter estimation, and initial conditions in their quantitative model.

Model evaluation. The discussion of model evaluation was limited to whether participants regarded the future growth projections as reasonable.

Policy design and evaluation. Their policy design and evaluation focused on scenario specification and analysis, rather than the efficacy of specific policy actions to mitigate the negative impacts of climate change. They used stakeholder input to develop scenarios to evaluate factors believed to be important determinants of future national poultry production, including assumptions about variables such as population growth, the evolution of the average size of poultry operations, and the future evolution of maize production.

Outcomes of the PSM process. They concluded that the PSM process informed stakeholders about the relative importance of key drivers of change, including climate, demographics, and economics. The PSM process identified that many drivers are outside the control of Nigerian poultry stakeholders, such as trade policy, consumer preferences, and a changing climate. Nevertheless, the quantitative model was useful for exploring future uncertainties and highlighting potential mitigating actions by stakeholders (e.g., reducing heat stress and switching from maize to cassava as poultry feed due to the latter's greater climate resilience). They state that the PSM process also facilitated collaboration and social learning among stakeholders in the poultry value chain; surveys conducted after each workshop indicated a statistically significant increase in systems thinking and awareness of future drivers of the poultry value chain's development.

3.4 Extension of PSM methodological boundaries

The process described above is typical of PSM, given its focus on one value chain at the national level, but other studies offer relevant methodological extensions. Anderson et al. (2019) note that a singlecommodity value chain may not adequately represent the interactions that likely affect food security outcomes, suggesting that a multiple-commodity approach (which they describe as a *value web*) may be more appropriate. PSM modeling can incorporate multiple food products. Another issue is whether PSM processes are appropriate across diverse social and cultural contexts. The evidence is rather limited, but Kopainsky et al. (2017) employed an adapted version of PSM with small-scale farmers in Zambia and Browne et al. (2021) evaluated whether PSM methods were culturally appropriate, i.e., consonant with cultural ways of "knowing, being and doing" in Aboriginal societies in Australia. Both found that the approach was culturally appropriate and promoted learning.

Another variation of the PSM approach, *Community-Based System Dynamics* (Hovmand, 2014) focuses to a larger extent on working with communities to address problems. Glickman et al. (2022) note that "CBSD specifically seeks to incorporate and center the lived experiences and wisdom of stakeholders and community members into the modeling process…CBSD participants build capacity in system dynamics and collectively create systems models themselves. In addition, CBSD emphasizes centering communities that have been historically marginalized within research and policymaking processes." The emphasis on developing additional capacity in communities and addressing historically marginalized groups may have relevance for PSM efforts focused on climate change and FNS.

Mumba et al. (2017) identify another potentially important consideration not often the focus of PSM research: modeling spatial interdependencies. Although they did not analyze FNS outcomes, they modelled intra- and inter-district dynamics of the animal disease East Coast Fever (ECF) in Zambia and noted that "the spatial aspects and interactions of socio-economic, cultural, and ecological drivers play a critical role in designing and implementing effective and sustainable community-led ECF control policies." Spatial interactions (and climate impacts that vary spatially) could be important considerations in future studies assessing FNS impacts.

3.5 Potential benefits of PSM application to food system governance

The PSM approach can support intentional food system governance by engaging relevant stakeholders, particularly when focused on food value chains. The benefits include flexibility, low cost and linkages to other conceptual frameworks.

Benefits of Involving Stakeholders. The involvement of stakeholders can enhance learning about the systemic origins of undesirable situations, build consensus about appropriate actions (interventions) to achieve collectively-desired outcomes, and provide motivation to undertake those actions. PSM processes also provide opportunities for co-learning and discovery, consistent with "double-loop learning" (Sterman, 2006) that can modify stakeholder mental models, systems structure, and decision rules. Stakeholders often also contribute to quantifying specific model parameters, leading to a more accurate representation of the system generating the reference mode behavior.

Involvement of stakeholders can contribute to improved communication, understanding of the causes and consequences of undesirable outcomes, and consensus for action by for-profit businesses, non-profit organizations, and governments. In some cases (e.g., Nicholson and Monterrosa, 2023), this led to funding for the implementation of interventions identified and evaluated through PSM. Rouwette et al. (2002) compared 107 studies using GMB in diverse contexts with stakeholders from for-profit businesses, non-profit organizations, and governments (but not addressing issues in food or agriculture). This review identified an increase in insight (generally defined as 'learning') about the origins of the problem as robust outcome of GMB: 96 of 101 studies reported a positive effect. Eighty-four studies described subsequent actions to implement results derived from GMB, and half reported a positive effect. More recent reviews of PSM case studies show similar positive impacts (Franco and Montibeller, 2010; Mingers and Rosenhead, 2004) on learning, consensus and motivation for action from GMB processes.

Scott et al. (2016) reviewed 45 studies that applied GMB from 1987 to 2014, finding that the strongest positive effects were on "insight," "commitment to conclusions," "communication quality," and "consensus," but that some GMB processes affected "decision quality" and resulted in "systems change." When GMB was applied to public health and healthcare issues, a systematic review (Estrada-Magbanua et al., 2023) found that nearly one-fifth of studies evaluated indicated that the process resulted in "systems changes" (e.g., organizational or physical changes involving production lines or personnel policies) and 12% resulted in "positive results of system changes" (e.g., desirable outcomes associated with model-informed policies and actions, such as increased profits or improved morale). However, Rouwette (2016) concluded that although "group model building does lead to changes in knowledge and behavior," but the underlying mechanisms have not been clearly identified.

To respond to combined nutrition and environmental challenges, "focus will increasingly shit to how such change happens, [and] the extent to which such complex systems can be 'designed' (and if so 'by' and 'for' whom)" (Andrew et al., 2022). The success of any change process requires a detailed understanding of the outcomes desired by value-chain stakeholders. Participatory scenario development (as in Olabisi et al., 2021) with PSM can help identify desired or undesired outcomes and support group learning about the dynamic processes of change. The tools used in anticipatory governance (e.g., Muiderman et al., 2022) also align with the PSM approach. Mason-D'Croz et al. (2025) discuss how GMB and other participatory approaches can broaden the range of futures considered and who gets to envision the future.

Benefits of PSM for policy identification, programmatic implementation design and monitoring. PSM is most frequently applied *ex ante* to evaluate and build consensus for potential interventions. Policy identification was noted in the discussion of SDM above as a key goal of PSM. As an example, Nicholson and Monterrosa (2023) used PSM to evaluate six strategies to increase the consumption of fruits and vegetables in urban Kenya, which resulted in funding for further value chain development activities identified as most effective to achieve that goal. However, the PSM process can also be used to plan the implementation of interventions and subsequent monitoring, evaluation, and learning. Newman et al. (2003) applied participatory SD modeling to inform strategies for malaria control in Bolivia and used quantitative modeling to track differences between observed and expected outcomes, which informed programmatic changes to improve performance. Fredericks et al. (2008) developed CLDs with state agency employees to evaluate a demonstration program for individuals with developmental disabilities, and concluded that the approach provided a "good decision support tool for a program evaluation [that] can help to explain policy implementation challenges and unintended consequences, show how compensating feedback loops can diminish the effectiveness of a policy or program over time, and illustrate how reinforcing feedback loops identify processes that may be difficult to control." Gerritsen et al. (2020) argued in the context of public health interventions, "If the goal is to produce models that can be used to generate action—as intended by the researchers in our study…more work needs to be done to ensure that the implementation aspects are given due consideration in the design phase of GMB research." This suggests a role for including implementation aspects in PSM analyses of interventions to address climate change impacts on FNS, which may involve relevant linkages with concepts and principles from "implementation science" (e.g., Tumilowicz et al., 2018).

Other benefits of PSM. PSM applied to value chains can be undertaken relatively quickly and at a low cost, and if not considered useful by a relevant set of stakeholders, the process can be repeated with appropriate modifications, or an alternative analytical approach can be implemented. This can provide a substantial benefit compared with large-resource global modeling tools developed over many years—tools that are not always appropriately applied because organizations become invested in their use and further development. There is a conceptual overlap between PSM and other methods used for foresight analyses, including Theory of Change (TOC; Thornton et al., 2017) and Program Impact Pathways (PIP) used in nutrition programming (Kachwaha et al., 2022). The adaptability of PSM facilitates its integration with global research, action, and policy agendas (e.g., the UN Framework Convention on Climate Change). PSM is also consistent with the principles elucidated recently by international organizations with a mandate to support food system transformation, for example, FAO, which noted that "Business-as-usual is not solving interconnected problems like food insecurity, malnutrition and environmental harm," concluding that "a systems approach is essential for transforming agrifood systems" (FAO, 2025).

3.6 Potential challenges for PSM application to food system governance

As with any analytical approach, there are challenges and limitations to the application of PSM. Potential challenges include lack of information and data, multiple and sometimes conflicting objectives and power differentials among stakeholders, representing the full complexity of food systems, contrasts with other common methods used to generate evidence about nutrition program impacts and clear identification of who benefits from a PSM process.

Data availability. Poor data availability and quality are problems across all modeling approaches in LMIC contexts, limiting the ability to conduct quantitative analyses. Information is limited about climate impacts on value chains, the costs and benefits of adaptation alternatives, and determinants of FNS. Information within the scope of day-to-day experience (such as that known by stakeholders) is less constrained and accessing it provides an important motivation for a participatory approach to conceptual and empirical model development. PSM can often address data limitations by focusing on the determinants of a specific reference mode behavior, using structured facilitation scripts to guide stakeholder discussion (Andersen and Richardson, 1997), and integrating data from both stakeholders and the extant literature. In addition, systems model results are typically sensitive to only a small number of feedback loops and their associated data inputs (Sterman, 2000). Thus, the model structure itself provides a mechanism to determine which information requires a higher degree of accuracy. Given PSM's flexibility in integrating quantitative, qualitative, and distributed systems knowledge, it may be better suited than other approaches to addressing data challenges.

Working with stakeholders. Establishing effective partnerships with stakeholders for any group exercise can be challenging. Stakeholders can be motivated to participate in PSM when they perceive potential benefits; mitigating climate change impacts on a value chain may be broadly regarded as beneficial. Working with stakeholders to reach a consensus on understanding and priority actions can be time-consuming, although the benefits of PSM may offset the costs. In addition, challenges exist in ensuring that all relevant stakeholders participate and that facilitation methods are context-sensitive to provide full participation by marginalized groups (Stephens et al., 2026). Strategies to help ensure that power dynamics are appropriately addressed include practices for stakeholder selection, workshop structure, and facilitation techniques. Nicholson and Monterrosa (2023) worked with local partners to identify appropriate stakeholder participants in their study of vegetable value chains in Kenya. When gender power dynamics are a potential issue, initial workshops can be conducted separately for men and women (Jagustović et al., 2021). Facilitation that seeks input through written forms (e.g., post-it notes) and divides participants into smaller working groups can help ensure that the perspectives of all stakeholders receive appropriate recognition (Hovmand, 2014). Finally, maintaining focus on developing the best possible understanding of the system origins of the reference mode behavior can also mitigate power dynamics by shifting the focus from individual opinions or personalities to system outcomes (Black, 2013).

Complexity of food systems or value chains. Value chains include multiple actors, each with unique incentives. This complexity can be addressed in PSM through focus on the *reference mode behavior*, which defines collectively-desired improvement and helps reduce the number of variables included in the conceptual or quantitative models. The PSM process also proceeds sequentially, typically beginning with the causes of the reference mode behavior, then its consequences (variables affected by the reference mode) and then the description of feedback loops linking causes and consequences. Sequential development of complex systems structure improves participant understanding and ownership of the process (Vennix, 1996), and sequential display of key relationships (or feedback loops) facilitates discussion and understanding in sessions seeking stakeholder feedback on CLDs and quantitative modeling results. Choosing an appropriate level of aggregation for concepts contributed by stakeholders and using standard diagramming techniques (e.g., Mui et al., 2019) also help facilitate understanding and ownership. In the quantitative analysis phase, SDM focuses on 'dynamic complexity' (how short-term and long-term outcomes differ), rather than on 'detail complexity' (mapping out all possible combinations of interactions), which also can appropriately limit model scope. The complexity of food systems and value chains should be seen as a motivation for using systems modeling approaches rather than an impediment.

Contrast with common methods of evaluating programs to improve FNS. PSM contrasts with typical analytical approaches for assessing the effectiveness of nutritional interventions. Observational or experimental approaches to evaluating single-exposure, single-outcome linkages are common. Nutrition interventions have become increasingly complex in recent decades, and programs now entail multiple inputs and multi-arm experiments that compare outcomes from multiple interventions to one control group. PSM can complement existing conceptual approaches to analysis used to identify high-leverage interventions to improve FNS outcomes., such as Directed Acyclic Graphs (DAGs), which are used to represent hypothesized causal relationships for statistical analyses and study design (Digitale et al., 2022). The central question for DAG analysis is whether a statistical relationship exists between variables. In contrast, the systems modeling component of PSM focuses on how the hypothesized or documented relationships between variables (i.e., system structure) lead to system behavior (e.g., FNS outcomes). PSM, therefore, highlights the broader implications of relationships and provides relevant information about the potential to implement interventions in a dynamic systems context.

Can PSM drive improvements in FNS and for whom? One objective of applying PSM is to facilitate meaningful changes in value chains for a set of target beneficiaries who are more vulnerable to the negative impacts of climate change on FNS. PSM can facilitate the actions decision-makers need to implement systemic change by developing consensus on desired outcomes and required actions. Model development with stakeholders is only one component of processes to support action. Identifying implementation pathways (what actions need to happen, when, and which actors undertake them; Tumilowicz et al., 2018) for potentially disruptive interventions is crucial. PSM can quantify trade-offs among stakeholders and identify potential mitigating actions.

4 Implementation of PSM: lessons learned and evidence of impacts

A plethora of systems-oriented methods exists for identifying and assessing potential interventions to address climate change and FNS outcomes (Peters and Thilmany, 2022), so it is relevant to provide evidence regarding the application of PSM. To our knowledge, PSM with a focus on value chains has not yet been applied to identify and assess context-specific interventions to improve FNS outcomes under climate change. We thus review previous literature to provide less direct evidence on impacts and key lessons from the application of PSM and systems approaches in other contexts. Although not designed to be a comprehensive or systematic review, we summarize (a) studies on the effectiveness of GMB and PSM, (b) lessons from PSM application to FNS outcomes, and (c) lessons and motivations for systems analytical approaches to food system governance.

4.1 Applications of PSM to the analysis of FNS

The potential for actionable insights into FNS under climate change can be informed by a review of previous studies that used PSM methods. An initial literature search identified no previous studies that used PSM to address climate change impacts on FNS and with an emphasis on value-chain scale analyses. A small but growing number of studies have applied PSM to FNS research questions. Many of these studies were published during the past 10 years. At present, the most common themes in this research are healthy diets and obesity (i.e., they are focused on public health nutrition rather than FNS), and many of the studies are from higher-income countries rather than LMICs. Many studies develop only conceptual diagrams with stakeholders, although a few (e.g., Glickman et al., 2022) indicated that subsequent quantitative modeling would be undertaken.

Several studies have developed quantitative SD models as components of the PSM process, although not all focused on value chains or FNS. Heffernan et al. (2017) and Roberts et al. (2019) focused on public health nutrition rather than FNS using quantitative SD models of childhood obesity in Australia. de Leon and Kopainsky (2019) used the PSM process to evaluate policies to enhance resilience in two districts of Guatemala, with a focus on food security outcomes. They found that stability in food systems is mainly driven by key strategic resources that moderate the effects of environmental changes on food availability and affordability. The Nicholson and Monterrosa (2023) study of the vegetable value chain in Nairobi, generated additional resources for the implementation of priority interventions and for an additional study of consumer preferences for vegetables (Li et al., 2024).

One study more closely related to the objectives of this paper is Jagustović et al. (2021), which involved stakeholders in the development of an SD simulation model of a climate-smart village (CSV) in northern Ghana. This model incorporated population dynamics, land use change, biomass availability, maize production, greenhouse gas emissions to assess short and long-term synergies and trade-offs at the household level. Their analyses suggested that neither maize yields nor months of adequate household food availability (their metric of 'food security') could be maintained through 2060, despite short-term improvements due to the adoption of climatesmart production practices. Although it considered climate change impacts on production and migration, this model did not link to a broader value chain or consider impacts on nonagricultural households.

Overall, the evidence about the impacts of PSM as applied to the analysis of FNS appear similar to assessments of GMB noted earlier. For example, Calancie et al. (2022) found that using GMB within the context of a community-based committee working to address a nutrition issue (obesity) helped group members "see new perspectives, appreciate complexity, commit to prioritized actions, and influence their broader networks." For these reasons, they noted that GMB "may be useful when groups are determining effective, feasible priorities for whole-of community interventions."

4.2 Applications of systems approaches to food system governance

Systems concepts have become more closely linked to food system governance over the past decade, though the connection is sometimes only implicit (e.g., Queenan et al., 2020; Francisco et al., 2023; Liu et al., 2024), and there have been only a limited number of PSM implementations focused specifically on governance. In a review of literature on food system governance, Hospes and Brons (2016) noted that although much of the literature discusses generic properties of a system, such as the components, linkages, boundary and scale, they identified little conceptual work that "integrated and elaborated on governance in definitions and frameworks to analyse the complexity and dynamics of food systems." Brzezina et al. (2016) noted in an analysis of the potential for a transition to more organic farming in Europe that it was not sufficient to "identify specific actions and policies for increasing the resilience of food systems" and that the design and implementation of interventions requires "careful consideration of political agency…and negotiation of power relations." Leeuwis et al. (2021) echoed this perspective, emphasizing that changing the trajectory of food systems requires more than obtaining a science-based understanding of how system components interact. Rather, it must address competing views of system boundaries and purposes, and often-limited possibilities for centralized governance. They highlighted the need to "look for approaches that anticipate and accommodate inherent social tensions and struggles in the process of changing food system dynamics and outcomes." Katina et al. (2020) noted that modeling and simulation approaches can be useful for "complex system governance" although they focused on a review of methods rather than their application.

Kopainsky et al. (2015) provide an example of PSM integrated with the Socio-Ecological Systems conceptual framework to examine how alternative approaches to food system governance could achieve a better balance between food provision and environmental outcomes in Switzerland. They used stakeholder input to modify a global system dynamics model of food security and environmental outcomes to the Swiss context. Stakeholders from Swiss federal ministries, agricultural research organizations, farmer organizations, extension services, the food processing industry, and consumer organizations defined the main outcome indicators and provided data for model formulation. Stakeholders also specified and quantified scenarios and policies and discussed policy implications. Their analysis indicated that yield improvements and the implementation of more sustainable production systems could increase food production and improve environmental performance. However, they noted that "these fields of action need to be complemented by fields of action outside agriculture, such as reductions in food waste and losses or changes in consumption patterns."

Bianchi et al. (2020) noted that systems thinking and collaborative governance are relevant to public policy and design because "in today's complex, plural, and fragmented governance settings, a single organization can manage only a subset of the resources affecting the wider system outcomes." To address this governance challenge, the use of system principles to frame problems and to identify, implement and assess interventions will be helpful, particularly when "deployed in a group setting or when key stakeholders are otherwise engaged." They emphasize that a process like PSM can facilitate building the consensus needed to support and sustain the implementation of recommended actions.

5 Priorities for moving PSM to scale for food system governance

The threats posed by climate change to FNS are growing, and the need to develop actions to both mitigate and adapt to climate change is increasingly important. However, the current approaches to anticipatory food governance (Muiderman et al., 2022) are failing to consider one of the most important scales of analysis, i.e., the value chain. PSM has potential to close this gap. For PSM to become an effective addition, we must better understand its domain of applicability—what questions can PSM answer effectively and in what contexts. To this end, we believe that a future research agenda for PSM should focus on the following key steps:

(1) Develop case studies using PSM in different LMIC settings that link FNS outcomes and potential climate change scenarios;
(2) Synthesize and communicate best practices for the varying uses of PSM, including how to apply it for both learning support and as a decision support tool for project design, prioritization, and implementation and monitoring exercises;
(3) Target PSM to assess food access metrics for key groups (e.g., farm households vulnerable to climate change or low-income urban residents).

Given the multidisciplinary nature of FNS, the design and implementation of these case studies would be best carried out by a consortium of researchers from different disciplines and with diverse regional experiences. The case studies using PSM in different LMIC settings could be embedded within existing projects or conducted as stand-alone projects. Their design and implementation should be coordinated to ensure consistency and rigor in evaluating the impacts on knowledge and action. The cases could address the same issue across different geographic regions, or different issues within the same geographic region. (For example, our group has proposed coordinated case studies on vegetable and dairy supply chains in Kenya, improving the proportion of children in rural Zimbabwe who meet Minimum Acceptable Diet criteria, and assessing strategies to reduce childhood exposure to aflatoxin in the maize- and groundnut-based diets of Tanzania.) Funding interest may come from a variety of sources, including government entities (e.g., the U.S. National Science Foundation; Dutch Official Development Assistance), international bodies (e.g., FAO, UNICEF), or foundations (e.g., the Gates Foundation), each of which has supported or expressed interest in individual PSM projects. The case studies can be evaluated based on measures typical of PSM processes (learning, consensus, awareness of systems drivers) but also on whether they generate stakeholder behavioral change (for example, additional funding allocated to solutions identified by the PSM process as high-leverage). Although PSM processes are designed to be contextspecific, system issues, structures or solutions common across the cases may facilitate their reuse and dissemination.

One challenge we have experienced is that PSM is not well known among many analysts and practitioners in food and nutrition, who thus prefer to fund more traditional approaches to program design and implementation. Documenting and disseminating knowledge about the benefits and limitations of PSM is therefore crucial to its broader acceptance. Another challenge lies in broadening the capacity for PSM implementation, which requires both systems knowledge (key concepts in stock-flow-feedback dynamics and diagramming) and requisite group facilitation skills. University-based programs that teach these concepts are relatively few, and most are based in Europe or the U.S. Online programs exist and may support considerable learning about these concepts, although practical experience is essential. Funding to support capacity development for individuals from stakeholder groups and implementing organizations—and their involvement in the case studies—would strengthen the immediate outcomes of the PSM process and support long-term capacity development and scalability.

In sum, PSM provides an effective and flexible approach that can fill important knowledge gaps, particularly at the scale of the value chain. This approach aligns with previous conceptual frameworks, can incorporate multiple FNS metrics, facilitates assessment of effective value chain interventions, and builds consensus for action. We recommend the application of PSM to enhance our understanding of its strengths and limitations to help policymakers and beneficiaries identify and implement interventions to improve FNS outcomes under climate change.

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