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Perspective

Getting into the doughnut: A framework for assessing systemic resilience in the global food system

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https://doi.org/10.1016/j.oneear.2025.101460

SUMMARY

The global food system's recent disruptions reveal its vulnerability to cascading failures, highlighting the urgent need to strengthen its systemic resilience, a vital precondition for global food security. Though modeling is key to comprehending its complex behavior and informing policy and decisions, the conceptualization, assessment, and modeling of systemic resilience are still in their infancy, raising questions about the suitability of existing models for evaluating resilience-building solutions. Utilizing insights from complexity theory and systems thinking, this paper proposes a holistic framework of seven criteria to evaluate modeling approaches and policies for systemic resilience. An assessment of five existing modeling approaches and associated examples of existing models reveals important gaps in current methodologies, especially regarding the transmission and amplification of impacts on the macro scale. Hence, we call for enhancing the analytical preparedness capability through the development of new models and clear communication of current shortfalls to stakeholders for improved governance.

INTRODUCTION

Our global food system (GFS) is in crisis.[1] Multiple interacting shocks have brought the progress toward eliminating malnutrition to a halt,[2] with the frequency of disasters having increased significantly in recent decades.[3] Interrelated challenges, such as dietary shifts, climate change, and biodiversity loss, further increase risks for failure.[2,4–6] Especially for agriculture, a sector highly dependent on healthy ecosystems and suitable climatic conditions, the consequences of environmental degradation might be drastic and far reaching.[7] The impacts of systemic crises range from limited education and school dropouts[8] and rising poverty and inequality[9] to spiraling debt of net food-importing low- and middle-income countries (LMICs).[10] However, the most direct impacts are persistent hunger and malnutrition, which trap the world's poorest strata of society. Rising food prices lead households to afford less food,[9] as seen in the 2007–2008 food and financial crises when the number of people in hunger reached a record level of over one billion in 2009.[11] Similarly, COVID-19 added another 90 million hungry people in just one year.[12] Compounding the war in Ukraine, these effects prevail, with 58% of all countries experiencing increased shares of population in hunger than pre-pandemic (2019) and 77% in more slowly recovering low-income countries (LICs).[12] Malnutrition is on the rise as people switch to less nutritious, cheaper food, and cooking at home might be more expensive due to economies of scale and time constraints through additional workload.[9] Post-2021, 42% of the global population is unable to afford a healthy diet,[12] while there are enough calories produced to feed the world, with a global food supply of 2.985 kcal per capita per day in 2022.[13]

In light of these dramatic consequences and the persistence of hunger, building systemic resilience (by "resilience" we mean a capacity of a system to persist and maintain *existence* of the system function, following a disturbance; see the next section, "Complexity of the GFS and systemic resilience as an emerging property," for further discussion) within the GFS appears to be indispensable to achieve the Sustainable Development Goals (SDGs).[14] However, the capacities of the GFS for resilience are insufficient. Vulnerabilities for systemic failure, e.g., reliance on a few global chokepoints and susceptibility to self-propagation of disruptions, remain unaddressed.[15,16] Simultaneously, persistent inefficiencies and high inequality in food distribution leave millions vulnerable to shocks, while one-third of global production is lost or wasted.[17]The GFS's unsustainability jeopardizes its long-term functionality.[2] Mainly optimized for production efficiency and gains for a limited number of actors, it is the major driver of terrestrial biodiversity loss,[18] habitat destruction (80% of deforestation is attributed to the GFS[18]), anthropogenic nitrogen and phosphorous loading (approximately 90%), global greenhouse gas emissions (roughly 30%),[19] freshwater withdrawal (ca. 69%),[20] and pollution.[21] Furthermore, growing numbers of non-communicable diseases driven by obesity and under- and malnutrition pressure the viability of national healthcare systems[22] and stifle development perspectives.

Governance plays a key role in steering the GFS dynamics and creating conditions for positive development and change.[23]

However, its complexity poses challenges for standardized management solutions,[24–26] and limited understanding of possible behavioral responses may lead to policy failure.[25,27,28] As building resilience hinges on the ability to understand potentially counterintuitive systems' behavior arising from non-linear interactions, feedback, and delays within complex systems,[28,29] *ex ante* modeling may support the agency of decision-makers by uncovering possible strategies for positive change. However, the conceptualization and assessment of systemic resilience are still in their infancy, and the question of the applicability of existing modeling approaches remains unanswered. This calls for the development of an enhanced analytical capability to assess systemic risks and the viability of adequate policy responses. To address this gap, this paper introduces a framework of seven criteria capturing key system factors influencing risk on a global scale, on which existing GFS model approaches and models are assessed.

The following section starts with a short introduction to systemic risks in complex systems (CSs), explaining why reflecting on the GFS's complexity is key to understanding systemic resilience. This is followed by a derivation of bespoke systemic risk assessment criteria. Evaluating modeling strategies and a set of illustrative examples against these criteria, the inherent strengths and weaknesses of existing modeling approaches are discussed. We conclude with an outlook for future model development and policymaking based on the current understanding of systemic risks in the GFS.

Definitions employed in this paper

Global food system (GFS): We use the term "GFS" to refer to the complete nested structure, including parts which are not directly linked to global supply chains (see Appendix A in supplemental notes for a more detailed presentation of the food system).
Actors: Actors comprise all individuals or entities that engage in different food system sectors. They can be people, companies, and institutions (e.g., governments or regulatory agencies).
Dimensions: Dimensions refer to different areas in which food system outcomes can be measured, including food and nutrition (including food security and health), economic impact, social well-being, and environmental impacts.
Sectors: Sectors refer to the different clusters of activities within the food system. They comprise production, processing, packaging, storing, retailing, distributing, consuming, and disposing of food.
Outcomes: Outcomes are all ways in which activities within the food system are influencing themselves or the non-food environment.
Level: Level refers to a tier or layer within the hierarchical structure of the GFS, from individual level to international/global level.
Scale: Scale refers to the spatial, temporal, or organizational extent of the system considered, reflecting the breadth of analysis or intervention, e.g., the geographic area or number of people involved.

COMPLEXITY OF THE GFS AND SYSTEMIC RESILIENCE AS AN EMERGING PROPERTY

The GFS is a highly and strongly interconnected as well as internationally interdependent system,[30] consisting of a nested set of sub-systems ranging from subsistence farming to international cooperations and supply chains, affecting outcomes (e.g., diets), perceptions, and values globally. A system is defined by its components as well as their interactions (with individual parts, the system, and its history) from which emergent properties and outcomes arise.[31] When systems possess strong mutual interdependencies and correlations, resulting in interactions among subsets and mutual adaptation of elements, they experience organized complex behavior at multiple scales,[27,32] consequently introducing non-linearity; the system becomes more than the sum of its parts.[33] Emergent macro-scale properties (e.g., collective goals in agricultural production[34]), behavior (e.g., of international supply chains), and outcomes, such as food prices,[35] arise from interactions and interdependences of communicating and trading non-anonymous actors,[36] which are not organized or governed by a central control (with firms often not having an overview over their own supply chain[37]). *Risk* and *resilience* are such emerging properties of the GFS.

Example: Increasing risk of systemic failure through market consolidation and corporate control

The GFS is characterized by high market concentration and has been subject to an even larger number of merges and acquisitions than the rest of the global economy.[38] Six companies control 78% of the global agrochemical markets, six companies control 58% of the seed supply, and three companies provide nearly all the breeding stock for poultry.[39] Similarly, the four firms occupying 62% of the agricultural fertilizer market[39] were classified as a global oligopoly.[40] Simultaneously, land inequality is accumulating more and more land in fewer hands.[41] Despite dampening small fluctuations, consolidation, and strong correlation through similar strategies among large actors, exemplified by the recently launched initiative "Covantis,"[42] might make the GFS vulnerable to large-scale systemic shocks.[27,32] Furthermore, their horizontal integration into other markets like energy, plastics, shipping, and industrial chemicals,[43] as well as horizontal shareholding of a few giant investors,[39] may lead to risks of cross-contamination in cases of failure and so-called "hyper-risks."[26]

While different definitions of *systemic risk* coexist,[44] it is broadly understood as the "risk of a generalized failure or collapse of all the components of a system."[45] Systemic failure arises from crossing a tipping point after which instability and cascading impacts occur (externally induced or self-organized criticality), experiencing an over-critical perturbation or coincidence of several compounding shocks.[27] While dampened small-scale fluctuations create the illusion of enhanced stability,[32] strongly interconnected and interdependent systems often experience fast changes[26] and fat-tailed risk distributions with increased likelihood for catastrophic failure.[32,46,47] Self-organization within the system is critical to understanding cascading changes (technology transfer, knowledge diffusion, etc.) and risk (e.g., rationing under constrained output), critically depending on actors' behavior and heterogeneity.[48–50] Simultaneously, crises often create vicious cycles, increasing the vulnerability to future shocks, e.g., already poor populations using savings and credit to buy food, pushing them even further into poverty.[9] Furthermore, systemic risks and resilience require an understanding of the broader systems context, its interactions with the wider environment, and possible triggering events, which can be shocks or random fluctuations.[26]

Framing resilience: The 5 questions

Assessing the resilience of the GFS from a systemic viewpoint requires clarification of the following[51]:
(1) Resilience of what?
This perspective focuses on the resilience of the GFS.
(2) Resilience to what?
Single or multiple shocks and/or stresses that could lead to a systemic failure.
(3) Resilience from whose perspective?
Analytical perspective with a view to quantitative modeling of the GFS.
(4) Resilience over which period?
From now until time frames suitable for assessing intergenerational justice, e.g., 100 years.
(5) Purpose of the assessment?
Informing and guiding policy formulation at national or global level.

In this paper, we define the "systemic resilience" of the GFS as the capacity to prevent its collapse and ensure its key outcomes (economic, social, environmental, and food security) are sustained and sustainable despite the impact of stresses and shocks over time.[52] Contrasting mere robustness, sustaining its outcomes encompasses all capacities comprising resilience: absorptive coping and adaptive and transformative capacity with severe systemic shocks requiring flexibility and change in the system's functioning[52,53] (see Appendix A in supplemental notes for a more detailed discussion of the resilience definition).

METHODOLOGY

As risk and resilience emerge from the interactions within the systems, considerations to assess and build resilience within the GFS should be guided by reflection on the characteristics of its complexity. Simultaneously, underlying assumptions and simplifications crucially determine suitability and must be communicated to stakeholders, who may base their decisions on model-based projections.[25,54] This paper draws from *food systems research*, *complex systems theory*, *systems thinking*, and the *Doughnut*[55] framework (see Appendix A in supplemental notes for a broader description of each of these four underpinning components) to establish criteria for model assessment and policy appraisal.

Based on their relevance for risk occurrence, transmission, and impact identified from literature, seven criteria representing overarching categories of essential features of the GFS were identified (see Figure 1). For each criterion, associated features are highlighted through questions (Figure 2) that may be posed to models, by asking whether these aspects are represented, or policy interventions, by asking if these features were considered and addressed in policy design. Criteria and questions aim to provide a structured framework for stakeholders to systematically check for underrepresented features, paired with explanations highlighting their relevance and potential consequences of neglect. Being contingent on the question of systemic resilience, other criteria might be relevant for other questions.

THE CRITERIA

Criterion 1: Aim: Providing food sustainably

Current literature highlights the interlinked role of sustainability and resilience within the GFS. The *purpose* of the GFS is to enable human thriving by supplying *healthy, safe, and nutritious food* to all in an *environmentally, economically*, and *socially* sustainable manner.[56] Resilience is crucial for long-term sustainability but is not an end in itself; rather, it complements sustainability and is a necessary but insufficient condition for it.[5,57] Hence, the transformation of the GFS toward greater sustainability should be the ultimate goal of development,[57] while potential transition risks need to be considered and mitigated.

The GFS's sustainability is characterized by its ability to stay within the safe and just space between crossing planetary boundaries and falling short in social foundations captured in the Doughnut framework[55,58] (Figure 3). Orientation toward sustainability implicitly includes a normative perspective in resilience building, as mere resistance to change does not automatically imply desirability.[17,57] Persistence of actions causing undesirable system properties (e.g., unsustainable agricultural practices) and subsequently endangering its long-term functioning needs to be actively reduced.[17] Consequently, resilience building needs identification and visualization of synergies and trade-offs, clear communication, and coordinated action based on a shared understanding.[17,59,60]

The systemic resilience of the GFS is not an outcome but reflects its actors' capacity to react to shocks through self-organization and evolution.[53] Building systemic resilience of the GFS focuses on preserving and restoring its ability to maintain its outcomes in all dimensions (economic, social, environmental, and food security)[4,23] while guiding self-organization, structural change, and evolution during the transformation toward greater sustainability.[27] Hence, it requires constant development, adaptation to changing circumstances, as well as room for experimentation and failure at lower levels.

Criterion 2: Scope and scale

Researchers agree that food systems' resilience can only be understood in a multi-dimensional and multi-scale approach, including all *sectors* (production to waste) and *dimensions* (food and nutrition, social, economic, and environmental outcomes) of the GFS.[53,62,63] Despite this acknowledgment, studies are often based on data availability instead of a systemic approach[53] and are conducted at household or community level, concentrating on a specific socio-economic group, livelihood, geographic location, or ecological context.[5,53,62–64] While considering all sectors is critical (e.g., the "hidden middle" of the food system was found

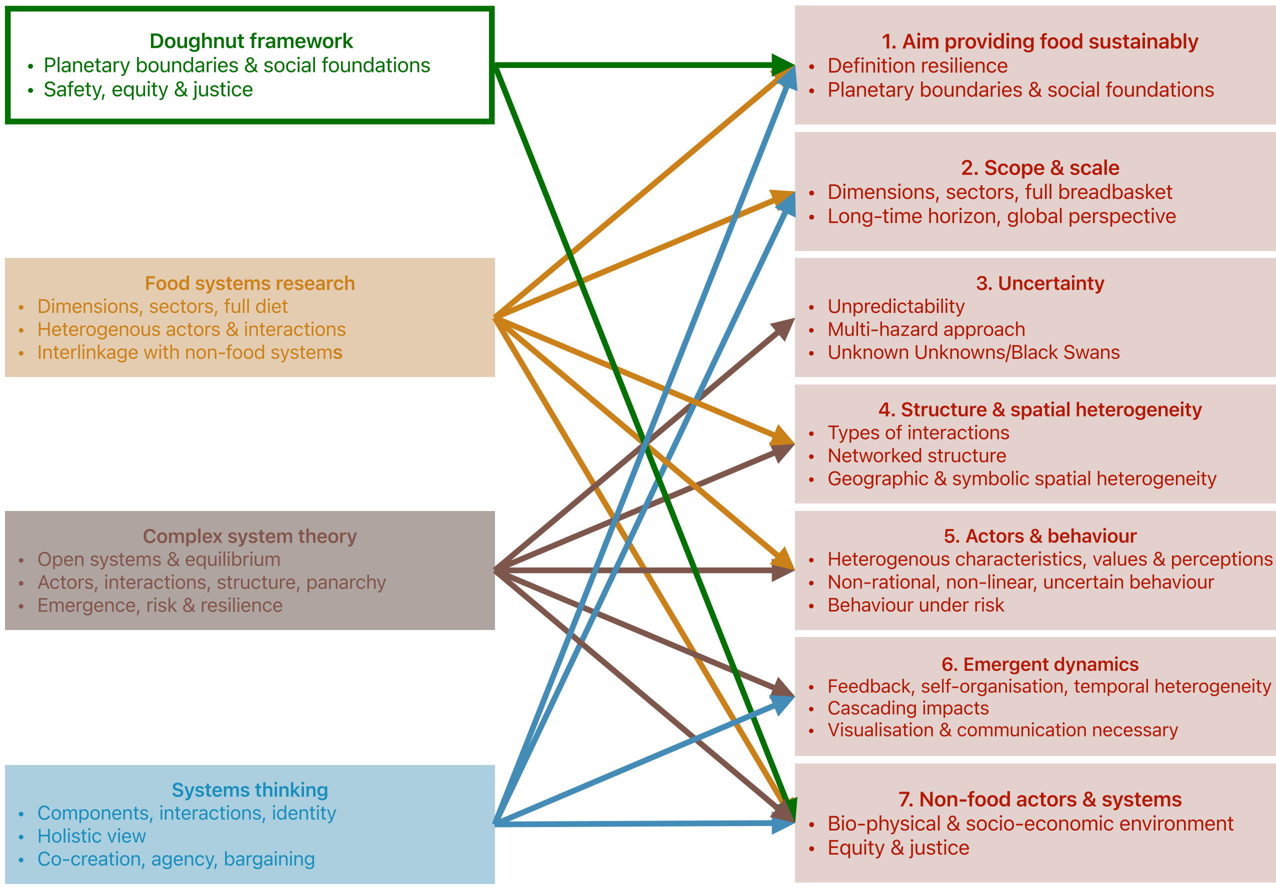

Figure 1. Theoretical foundations for the criteria of the GFS
The criteria are derived from three bodies of literature: food systems science, complex systems theory, and systems thinking. Doughnut Economics provides the framing of upper planetary limits and social foundations and highlights implications for safety and justice. Links indicate which literature each of the criteria draws from.

equally important to food security as farm yields in poor countries), discussions often focus on agriculture and trade.[65] Additionally, a prevalent focus on staple crops, neglecting other parts of the *breadbasket*, endangers understanding the full impacts of shocks.[6] Framing and enhancing resilience in narrow sectoral areas or for single actors misses feedback and can endanger the resilience of other actors or the overall system.[17,57,66] As an example, retailers might build resilience by using short-term, flexible contracts to easily switch suppliers and mitigate risk, which shifts risk to the producers.[59] Interactions and trade-offs between levels, sectors, and outcomes restrict the transferability of insights to different levels of the system,[63] naturally introducing issues of participation, equity, and justice[57,62], and should hence be considered explicitly.

High interconnectedness and dependence within the GFS require a *global perspective* capturing intra- and intersystem feedback in all outcome dimensions. Furthermore, a short time horizon overlooks the distant spatial and temporal feedback of interventions,[25,29] potentially leading policymakers and stakeholders to accept trade-offs that endanger the food security of future generations.[17] Hence, a holistic approach focusing on a broad range of outcomes for the whole society, considering appropriate *time horizons* (matching the time frame of self-organizing evolution and potential for self-organized criticality prevalent at the considered scale,[35] see the "emergent dynamics" criterion) is required.[17].

Criterion 3: Uncertainty

Uncertainty is inherent in living systems, as the evolving characteristics and interactions of components within biological and social systems introduce additional complexity compared to physical systems.[28,67–69] They entail (1) functional contingency and attribute selection through environmental interactions, (2) the emergence of new attributes and functions through creative and unpredictable evolutionary processes, and (3) individual variability among components of the same species.[69] Consequently, irreducible randomness[28] and unpredictable developments, such as innovation, lead to additional risk compared to systems with lower complexity,[26,70] further amplified by developments in communication and technology, spreading ideas, choices, and impacts of the individual across levels and scales (from local to global).[71] Hence, a deterministic view is unsuitable to cover resilience and might lead to management mistakes.[72] Instead, statistical treatment is necessary to simulate response to risk and policy-induced changes, while an iterative and adaptive approach is needed to account for unexpected behavior,

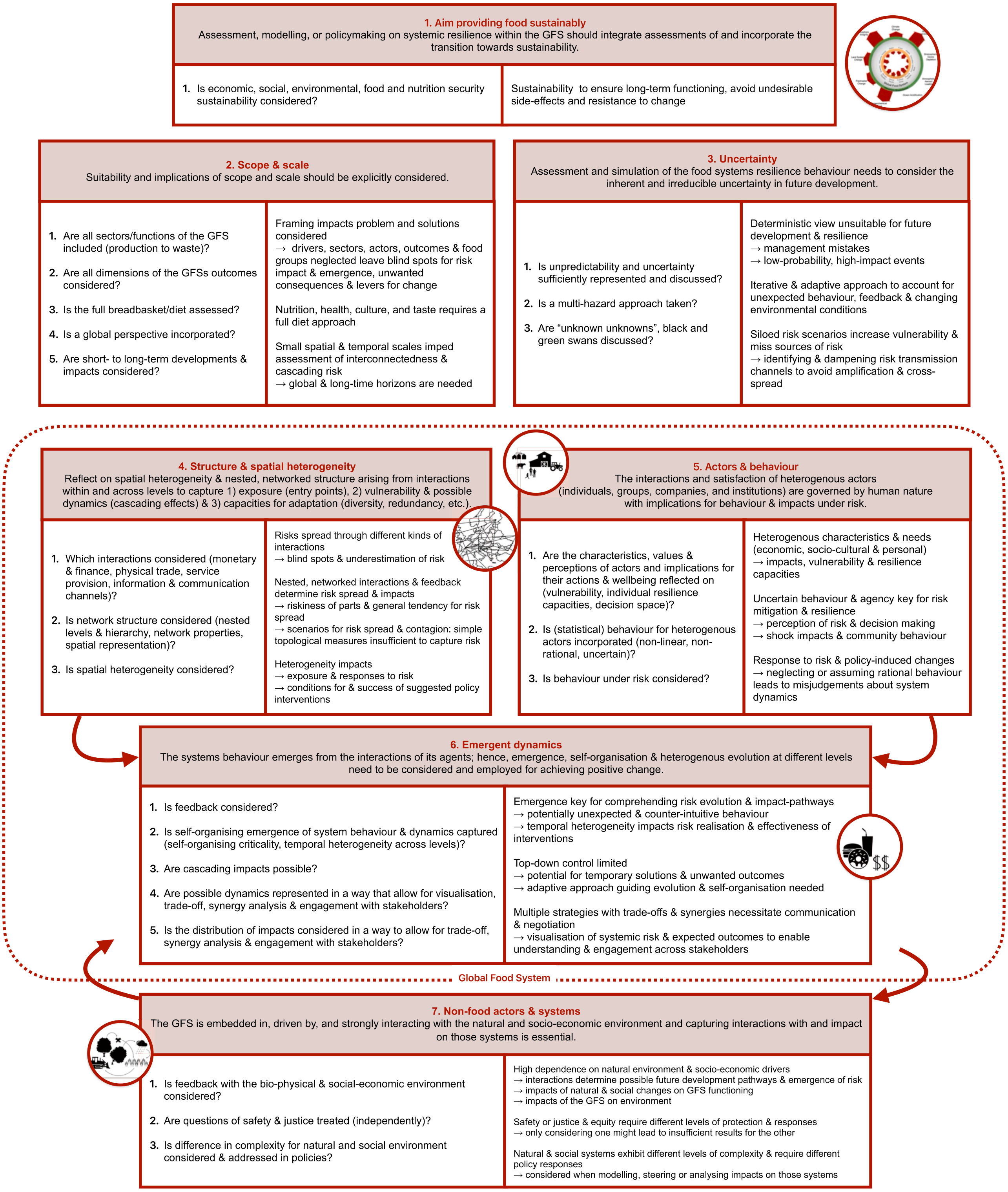

Figure 2. Seven criteria representing overarching categories of essential features for assessing the capability to capture resilience within the GFS

Each feature is presented as a question to guide model design and implementation, evaluate modeling strategies and results, and inform policy appraisal. The first three criteria (aim, scope and scale, and uncertainty) frame the research focus and direction. The remaining four (structure and spatial heterogeneity, actors and behavior, emergent dynamics, and non-food actors and systems) address methodological considerations, highlighting key features of the system relevant for risk transmission and resilience.

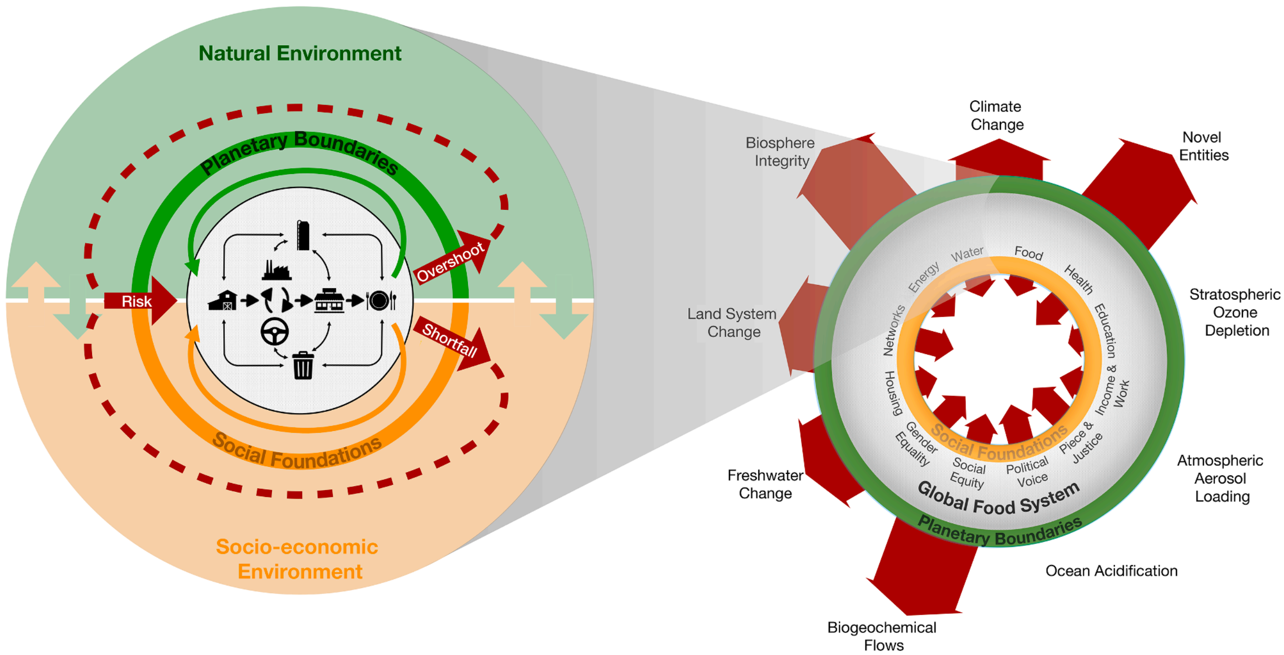

Figure 3. Sustainability-risk dependency: Unsustainability of the GFS driving systemic risk for GFS

The GFS's sustainability is characterized by its ability to operate within the safe and just space between crossing planetary boundaries and falling short in social foundations[55,58] (graphic adapted from Eker et al.[54] and Richardson et al.[61])—outcomes (food and nutrition security, social, economic, and environmental) need to be sufficient to enable human thriving for all, while not overexploiting planetary resources and services. Resilience is the ability to stay within this space despite the impact of shock and disturbances over time (right-hand side). As GFS outcomes impact its drivers and the planetary boundaries define the space in which Earth's functioning can be maintained in holocene conditions, overshooting them drives systemic risks to the GFS, e.g., from increased likelihood of drastic climatic or ecosystem change. Simultaneously, falling short in social foundations increases the risk for failure, such as food riots destabilizing national governance. Hence, the safe and just space, the "dough" of the doughnut, is the space in which the GFS can operate without driving additional risk (left-hand side).

feedback, and changing environmental conditions.[71,73] Furthermore, focusing on mean projections neglects the impact of potentially low-probability, high-impact events.[70]

Interconnectedness with human and natural systems and the nested structure of the GFS necessitate a multi-hazard approach, acknowledging uncertainty and identifying possible impact pathways leading to systemic risk.[5,73] Preparing against specific chains of events is not sufficient,[32,70] as it can increase vulnerability to unaccounted hazards.[74] As considering every possible risk scenario is impossible,[51] a major focus should be on enhancing adaptability and transformability,[74] as well as identifying and changing patterns, enhancing risk spread to limit contagion across parts.[26]

Criterion 4: Structure and spatial heterogeneity

Considering all relevant *kinds of interactions* within the GFS (financial dependence and price effects,[6,75] resource and supply dependencies, physical access,[6] lack of trust [e.g., food safety scares[76]], etc.) is essential to avoid blind spots and underestimation of risk spread. They are crucial to understanding (1) shocks and exposure, (2) general dynamics and evolution, (3) vulnerability, and (4) resilience capacities. A prime example is trade. With 85% of countries having low or marginal food self-sufficiency,[15] it is critical for risk and resilience, and increasingly complex, with more than 30 million direct trade connections related to the GFS and 22.2 trillion tkm food miles of final consumption in one year.[77] However, long-distance feedback and dependencies may well be hidden and unexpected,[4,78] e.g., 40% of the present-day participation in some arid regions in Eastern Africa is affected by irrigation-based agriculture in Asia.[79]

These physical and non-physical interactions among actors give rise to *structural properties*, such as connectivity, redundancy, diversity, and inclusiveness.[15,26,57] Capturing the topology and dynamic behavior of components (across the panarchy, which describes the dynamical organization and structure of the system,[80–83] and with the wider environment) is key to understanding the GFSs dynamics[35,47,84] and identifying leverage points enabling positive evolution toward resilience and sustainablity.[71] Increasing system size, reduced redundancies, denser networks, and a high pace of innovation and change may lead to increasing instability,[26] with high interconnectedness often mentioned as a key determinant for cascading risks.[15,26,48,85,86] Topology (networked interactions) and feedback influence the riskiness of individual parts to the system,[15,87] the general tendency for and consequences of risk spread.[26,88] Hence, knowledge gaps limit the ability to create scenarios for risk spread and contagion.[26,73,89]

However, research indicates that simple topological measures alone may not sufficiently capture vulnerability to cascading risks,[88,90] but self-organization within the system is critical.[48–50] Supporting self-organization for improved systemic resilience across the panarchy of the GFS entails understanding and balancing the resilience and vulnerability of different levels.[26,74,91–93] While lower-level processes are constrained by higher levels (government enforcing production standards, etc.), resilience on higher levels is driven by the dynamic behavior of lower levels (e.g., resilience of a country is impacted by the resilience behavior of the individual farmers).[5,26,53] However, if information/material flows to higher levels are sustained, lower levels may experience failure, experimentation, and learning without endangering the overall functioning of the system.[71] For example, supported small-scale trials of new farming methods to identify more suitable crops under changing climate conditions might be crucial to enable reaching long-term production goals without endangering the overall productivity.

Furthermore, accounting for spatial heterogeneity is key for assessing exposure and responses to risk, as well as the success of suggested policy interventions.[94] There are two dimensions to spatial heterogeneity: physical geography, such as climate or prevalent ecosystems, and human geography influencing symbolic structures, including structures of (1) signification (myths, paradigms, and ideologies), (2) domination (power and resources), and (3) legitimation (norms, rules, routines, and procedures).[81,95] These heterogeneous features impact the decision space of actors and might lead to unwanted consequences or policy failure if neglected. This is exemplified by programs aiming at women's empowerment through cash transfers (e.g., enhancing food security), which might increase intimate partner violence if intra-household dynamics, socio-economic situation, and prevalent gender regimes are not considered.[96].

Criterion 5: Actors and behavior

Accounting for *heterogeneous characteristics* and *non-rational, uncertain behavior* of actors is key for risk mitigation and resilience building, as they impact individual vulnerability and risk perception, resilience capacities, shock impacts and transmission, and community behavior.[36,97,98] The GFS consists of a diverse range of actors involved in food production, processing, packaging, transport, retail, consumption, and waste management, ranging from individuals to multinational companies.[60,99] Even within the same sector, heterogeneity is very large, as in agriculture, where the top 1% of the global farms operate 70% of the global farmland, while 84% of all farms are smaller than two hectares.[41] Considering these heterogeneous economic, social, cultural, and personal aspects is key for understanding vulnerability and impacts on human thriving.[55] Shocks, like the 2007–2008 crises, disproportionately increased poverty among the already poor, with less impact on overall debt headcount.[9]

Diverse expectations, anticipation, cognitive complexity, learning history, memory, and path dependence, subjective interpretations of reality, preferences, perceived value, intentions, conflict of interest, and power dynamics are all highly contextual factors influencing non-rational, heterogeneous, and inconsistent decision-making, communication, and responses to complex, often ambiguous and imperfect information, driving the emergent overall system behavior.[26,28,84,100] Especially, *under risk* actors might engage in irrational behavior, e.g., when countries, faced with an acute crisis, engage in hoarding and panic buying, worsening global shortages of specific food items and amplifying price spikes.[15,101,102] Furthermore, consciousness and perception of possibility enable actors to directly influence the evolution of the system,[69] such as increased sales expectations, which might drive a company to expand into another market, impacting food security as well as nutrition outcomes in this region.

Criterion 6: Emergent dynamics

Capturing *feedback*, *cascading risks*, and *self-organizing criticality* is essential for comprehending emerging properties of the GFS, such as stability, risk evolution, and impact pathways.[98] In open complex systems such as the GFS, interactions among parts sustain a dynamic equilibrium through permanent *feedback* in adaptation to changing outer circumstances; a static, stable equilibrium state does not exist.[103] Furthermore, different levels within the nested hierarchy of the system are evolving at different speeds with strong implications for stability, innovation, and resilience.[35] Stability arises from continual learning, adaptation, and transformation (e.g., adapting to changing patterns of rainfall or new regulations)[100] and critically depends on the whole system's characteristics and interactions with the environment. Hence, it cannot be captured by solely looking at individual components or initial conditions.[31,104] This is similarly true for understanding systemic risk spread[5,62,63]; focusing on sub-parts impedes recognition and estimation of *cascading effects*.[105] Direct losses are often insufficient to measure disaster impact due to upstream and downstream propagation and consequent amplification of true losses,[106] for example, though rising protectionism (export bans), panic buying, currency depreciation of food-importing countries, commodity speculation, or delayed transformation toward more sustainability.[102,107] Furthermore, the system is exposed to internal risks and *self-organizing criticality*, as outcomes of the GFS are simultaneously affecting its drivers, such as nature degradation, economic outcomes, lifestyle choices, climate, and land-use change.[7]

Recognition of emergence and *visualization* for understanding and communicating dynamics is key to enabling resilience building and management of the GFS, as the wide range of possible behaviors and spatial and actor heterogeneity impedes standardized management solutions.[26] Emergence significantly reduces the applicability of top-down resilience control as feedback, delays, and non-linearity give rise to multiple behavioral states, which are often counter-intuitive and might lead to unintended consequences.[25,26,29] For instance, government-guaranteed crop prices, intended for stabilization and farmer safety, can incentivize the cultivation of high-revenue, yet less climate-resistant crops, which may elevate vulnerability and instability over time.[35] Simultaneously, change of systemic features and negative feedback at higher levels can dampen the amplification of fluctuations[35,108] to stop cascades early and avoid catastrophic consequences before losses outstrip the system's capacities for recovery.[26] Hence, visualizing and discussing possible dynamics, as well as an actively adaptive approach, are key to avoid linear policies or temporary solutions creating a greater number of escalating problems in the future.[71] Furthermore, interventions should enhance adaptability and self-organizing evolution to achieve independence from stakeholders' ability to foresee future hazards and change,[32] e.g., through the establishment of a diverse backup system, limiting system size and connectivity or enhancing diversity within components for strengthening healthy competition, cooperation, and evolution.[26,32] Lastly, multiple strategies with trade-offs and synergies between actors necessitate engagement, communication, and negotiation across stakeholder groups for identifying solutions and acceptable tolerances of risk.[59,62,109,110].

Criterion 7: Non-food actors and systems

The GFS exchanges direct feedback with its surrounding systems. It is highly dependent on favorable *environmental conditions* and *ecosystem service provision*,[4] which are prerequisites and foundations of economic prosperity, human health, and well-being, which is typical for social systems.[111] This is exemplified by agricultural yields, which result from the intersection of management strategies and natural systems.[112] Furthermore, it is strongly impacting and driven by *socio-economic* developments (population growth, geopolitical stability, etc.).[4] For example, the GFS is estimated to contribute roughly $10 trillion USD to the global GDP.[22] Understanding and accounting for these dependencies is essential for estimating possible future development pathways and emergence of risk, covering (1) impacts of natural and social changes on its functioning (tipping points, etc.) and (2) impacts of the GFS on its environment.

It is crucial to recognize that the boundaries of the GFS are defined by the observer, reflecting their mental perceptions along with disciplinary, methodological, and theoretical frameworks.[25,113] While the limited ability to model reality and feedback forces labeling certain events as exogenous, it does not imply independence or unaffectedness.[25,29,68,70,114] Instead, overly restricted boundaries excluding spatially and temporally distant interactions hinder the understanding of risk and resilience. For example, "external" crises can significantly affect the GFS, as seen during the 2008 financial crisis, when speculators flocked into commodity markets, contributing to the food price spikes visible in this period.[11] Consequently, defining boundaries necessitates challenging assumptions, considering and monitoring exogenous and excluded variables, and involving relevant stakeholders in the process.[25] This is especially important as conditions enabling *safety* (long-term functioning) and *justice and equity* (distribution of gains, risk and impact bearing, potential to recover, etc.) require different degrees of protection and responses and should be considered individually.[55,58]

Interactions of the GFS with natural and social systems are associated with different kinds of risk and strategies for mitigation due to their different degrees of complexity and influenceability,[28,67–69] which need to be considered when managing interactions with those systems.[67] Physical systems, such as the earth's atmosphere, provide clear solutions to decrease risk, e.g., limiting CO_2 emission to avoid crossing of climate tipping points (melting of the Earth's ice sheets, collapse of the Amazon rainforest, etc.), with irreversible and far-reaching consequences forcing humanity to adapt if these risks are not mitigated.[115] In contrast, dynamics of social systems are more complex to stir due to actor heterogeneity and increased uncertainty.[69] However, distinct features of social systems, such as perception, creativity, and innovation,[28] may help to find multiple solution strategies and influence development pathways in a more direct and adjustable way.[69]

ASSESSMENT OF MODELING APPROACHES

> Models fail because more basic questions about the suitability of the model to the purpose weren't asked, because a narrow boundary cut critical feedback, because we kept the assumptions hidden from the clients, or because we failed to include important stakeholders in the process.—John Sterman (*System Dynamics Review*)[25]

Models play an important role in policy design by guiding expectations of the future, identifying possible and desirable intervention strategies, and providing evidence of policy impacts.[28,35,50] Moreover, modeling GFS dynamics under systemic risk may support systematic exploration of the core dynamics, possible behaviors, and emergence of risk, identification of core uncertainties and knowledge gaps, data collection guidance, hypothesis testing, demonstration of trade-offs, synergies, and options for interventions, training stakeholders, and informing the policy dialogue.[28,116] While inherent internal variability and model uncertainty hinder prediction,[117] modeling risk and resilience may quantify system responses to "what-if" scenarios. As an analytical tool, models may simulate how different conditions relate to possible system states and behaviors,[28,50] mainly identifying the emergence of adverse outcomes and their prevention under risk, linking today's choices to observed long-term outcomes and testing possible interventions.[98] However, modeling and simulation demand caution, as quantitative predictions might convey the illusion of precision and knowledge while hiding uncertainties and assumptions, with serious implications for policy analysis or decisions on acceptable future pathways.[118] While validation of models is difficult (GFS's internal variability, limited data, risk of overfitting, and inability to scan the full parameter space or perform large-scale experiments), collective agreement may not ensure suitability due to developers' shared backgrounds, prevailing schools of thought, tendency for consensus-seeking behavior, and herd effects in science.[28,119] Generally, models that can dynamically visualize development and changes in simulated outcomes offer an advantage, as they allow assessment of both predicted outcomes and the feasibility of simulated pathways. To reflect on the assumptions and limitations inherent to each model, results of different modeling techniques might be combined in a pluralistic[120] or possibilistic[121] modeling approach.[28] However, model discrepancy[122] and inability to capture the full space of possible models necessitate care and expert judgment, and an ensemble prediction might not necessarily ensure greater closeness to reality.[119,123]

All models are limited in some way; they may be assessed, *inter alia*, in respect to their accuracy matching past data, reliability and robustness, transparency, reproducibility, and fitness for purpose.[54] In contrast to commonly used data-driven assessments,[54] the criteria aim to highlight the theoretical underpinnings and identify whether a model is suitable for the assessment of resilience and whether it captures the qualitative behaviors influencing risk based on a problem-determined systems view.[28,78,99] The complexity of social-ecological systems, such as the GFS, hinders analytical solutions or purely statistical treatment.[35] Instead, models need to incorporate sufficient degrees of complexity to capture emergent behavior while being as simple as possible to enable understanding and communication.[32,71] This requires guidance to assess models based on their expected validity (or model skill[117]) in (1) understanding the emergence of macro-scale behavior from interactions of GFS actors, (2) implications of its complex structure for its management, (3) the role of coevolution (between different parts of the system) and path dependency, and (4) the need to address the

Table 1. Assessment of model types using the systemic criteria

Criterion	Equilibrium-based models (CGE, PE, DSGE, etc.)	IO	Network	ABM	System dynamics
3. Not optimization-based	n	p	p	p	p
4.1 Types of interactions	gr, fin, ser	gr, ser	gr, fin, ser, is	gr, fin, ser, is	gr, fin, ser, is
4.2 Structural properties and hierarchy	lp	lp	p	p	n
4.3 Spatial heterogeneity	lp	lp	p	p	lp
5.1 Actor heterogeneity and human thriving	lp	n	lp	p	n
5.2 Statistical rules of behavior	n	n	lp	p	lp
5.3 Behavior under risk	lp	n	lp	p	p
6.1 Feedback	lp	n	p	p	p
6.2 Self-organization and emergence of risk	n	n	lp	p	p
6.3 Cascading impacts	n	lp	p	p	p
6.4 Visualization of dynamic development	n	p	p	p	p
6. 5 Distribution of impacts	lp	lp	p	p	lp
7.1 Coupling with socio-economic environment	p	p	p	p	p
7.1 Coupling with natural environment and climate	p	p	p	p	p

Some criteria and questions are dependent on the particularities of an individual model and not on the model type, notably criteria 1,2, 3, and 7, and are hence not included in the model type assessment. Similarly, for the ability to include uncertainty, it is only assessed whether a model type is optimization based. n, not possible to represent the given criterion in the model; lp, limited possibility to include in the model; p, integration in the model is possible or state of the art. Detailed explanations can be found in the supplemental notes. For interaction types: gr, goods and resources; mon, monetary flow; ser, services; is, information and social interaction can be represented. Detailed reasoning for each assessment can be found in Appendix B in supplemental notes.

inherent uncertainty for decision-making (cope with variability, uncertainty, information gaps, and asymmetries).[94] The criteria aim to provide this guidance by allowing policymakers and practitioners to assess the suitability of models for systemic risk assessment from a methodological point of view. The quantification of resilience within the GFS is a relatively new field and is yet to be established.[57] Hence, capturing assumptions, strengths, and limitations to aid model development and classify estimates obtained with a given model type is essential.

We consider five modeling approaches: equilibrium-based, input-output, network, agent-based, and system dynamics models (Table 1), and assess at least one existing model to exemplify the use of the criteria (Table 2). As equilibrium-based models are widely employed[124–127] and computational general equilibrium (CGE) models are commonly utilized for long-term disaster impact analysis,[128] there might be a preference for these tools in resilience assessment. Capturing the long-term behavior of the GFS, several CGE,[129–132] partial equilibrium (PE),[133–136] and integrated assessment models (IAMs)[137,138] coexist. They quantify the GFS's influence on the natural environment and the economy, as well as the impacts of policies and climate change.[126] One strength of existing equilibrium-based IAMs is their ability to directly link physical models, for example, crop models, with the economy and other physical systems to capture dependencies,[139] as done in IMAGE[137] or MESSAGEix-GLOBIOM.[138] However, equilibrium- and optimization-based approaches impose several drawbacks for the assessment of risk and were sometimes classified as "fundamentally incompatible with probabilistic cascade effects."[26] The equilibrium assumption is challenged for several reasons: (1) assumed stability of balanced supply and demand experiencing no pressures for change[140] disagrees with the reality of an open, complex GFS requiring constant inputs to be actively maintained in a stable state far from thermodynamic equilibrium;[35,141] (2) curvature of demand and supply functions exclude positive feedback and cascading effects;[50] (3) shocks are bound to arise exogenously[140] as representing self-organizing criticality and cyclic behavior is not possible;[93] and (4) implicit assumption of optimal and full resource, labor, and capital allocation excluding the possibility of positive change.[50] Structural properties of the system, such as supply chains and hierarchy, are not covered in the macroeconomic equations governing the behavior. Furthermore, assuming non-interacting, representative agents maximizing their utility[140] is problematic for risk assessment due to (1) inability to capture emergence, path dependency, correlation of variables, and self-reinforcement within the system;[26,50] (2) being an incorrect representation of individuals' perception and attitudes toward risk and uncertainty;[142,143] (3) failing to account for heterogeneity in actor behavior, power dynamics, impacts on self-organization, and information transmission;[26,49,50] and (4) problems in representing distributional effects and full impacts of shocks (cannot represent individuals or companies).[144] Moreover, end-to-end analysis, excluding the pathway of the transition processes to a new equilibrium, causes limitations in accounting for full risk impact (higher degrees of vulnerability might be experienced during the post-shock transmission phase[145]), policy advice (e.g., offering normative solutions), and identification of possible leverage points for risk mitigation and positive change.[50,86,146,147] Additionally, management strategies that yield similar long-term

Table 2. Assessment of existing food system models with the criteria, highlighting individual strengths and limitations

	MAGNET (CGE)	IMPACT (PE)	GLOBIOM (PE)	MagPIE (PE)	IO	Network	ABM	FELIX (system dynamics)
Ref.	Woltjer et al.[129]	Robinson et al.[133]	Havlík et al.[134]	Dietrich et al.[149]	EXIOBASE based; see Sun et al.[150]	Laber et al.[151]	Colon et al.[152]	Moallemi et al.[153]
1. Sustainability assessment	y	y	y	y	possible but not yet done	n	n	y
2.1 Sectors included	production, waste, transport, processing, bioenergy	agricultural production, trade, processing (some value chains, limited), bioenergy	production, trade, bioenergy	production, processing, trade, transport, waste, consumption	production, trade	production (limited, countries just possess goods), trade, processing	transport, trade (Tanzanian exports and imports)	production, consumption
2.2 Outcome dimensions included	economic, environmental, food and nutrition security	economic, environmental, food and nutrition security	economic, environmental	economic, environmental	economic (potential for environmental and social)	economic	economic, food security (not explicitly included, only consumption loss)	economic, environmental, social, food and nutrition security
2.3 Full breadbasket	y	y	y	y	y	y	y	n
2.4 Global model	y	y	y	y	y	y	n (limited to Tanzania)	y
2.5 Time frame	flexible/long (usually 10 year time periods, 2050); time step: flexible	flexible/long (2050); time step: 1 or 5 years (depending on output)	flexible/long (2030, 2050, 2100); time step: 10 years	flexible/long (up to 2100); time step: 10 years	static model; changes over time not assessed	short time frame (results presented for 10 years); time step: 1 year	very short time frame (1–4 weeks); time step: 1 week	flexible/long (2015–2100); timestep: 0.01 years (output saved for each year)
3.1 Incorporation of uncertainty	scenario analysis, but based on mean projections	scenario analysis but based on mean projections	n	n	n	n	y (only uncertainty in supply chain network)	y
3.2 Not optimization-based	n	n	n	n	y	y	y	y
4.1 Types of interactions	goods and resources, services, trade, finance	goods and resources, trade	trade	goods and resources, trade, R&D finance	trade	goods and resources, trade	goods and resources, trade, services (only aggregated)	highly aggregated: goods and resources, information
4.2 Network properties and hierarchy	n	n	n	n	y (but no hierarchy)	y (but no hierarchy)	y (but no hierarchy)	n

(*Continued on next page*)

Table 2. *Continued*

	MAGNET (CGE)	IMPACT (PE)	GLOBIOM (PE)	MagPIE (PE)	IO	Network	ABM	FELIX (system dynamics)
4.3 Spatial heterogeneity	limited; spatial heterogeneity in input	limited; spatial heterogeneity in input	limited; spatial heterogeneity in input	limited; spatial heterogeneity in input	n	n	n	n
5.1 Actor heterogeneity and (individual) human thriving	n	n	n	n	n	n	limited (nodes not actors are heterogeneous in terms of consumption and sector representation)	n
5.2 Statistical rules of behavior	n	n	n	n	n	n	n	n
5.3 Behavior under risk	n	n	n	n	n	n	n	not directly included, but has been linked to behavioral framework to model dietary change under climate risk
6.1 Feedback	n	limited	n	n	n	n	y (but limited)	y
6.2 Self-organization and emergence of risk	n	n	n	n	n	n	n	n
6.3 Cascading impacts	n	n	n	n	possible but not yet done	y	cascading impacts from transport disruption within Tanzania	limited (sector cascades, but no supply chain or inter-country cascades)
6.4 Visualization of dynamic development	n	n	n	n	n	y	y	n
6.5 Distribution of impacts	country level: food security inequality (limited), spatial distribution	country level: food security, food demand, and welfare	country level: economic impacts subnational level: land-use change	country level: economic impacts; subnational level: land-use change	country level: spatial, sectoral, and supply chain	country level: spatial, sectoral, and supply chain	local level: spatial and sectoral distribution of losses within Tanzania	n
7.1 Coupling with socio-economic environment	y	y	y	y	n	n	n	y
7.1 Coupling with natural environment and climate	y	y	y	y	n	n	n	y

Models are selected as example cases and do not attempt to provide a comprehensive overview. Some criteria and questions are dependent on the particularities of how the individual model is used and not the model itself, notably criteria 3.2, 3.3, 7.2, and 7.3, and are hence not included in the assessment. Similarly, for the ability of including uncertainty, we included the additional question specific to modeling asking whether a model is optimization based. n, no; y, yes. Detailed description of the model assessment can be found in the Appendix C in supplemental notes.

sustainable outcomes in equilibrium might have very different impacts on the resilience of the system when it is far from equilibrium.[148] As the assessment shows (see Table 1), these modeling approaches are hence very limited in assessing systemic resilience within the GFS.

Boundaries between input-output models (IOs), networks, and agent-based models (ABMs) are subject to definition, exhibiting different degrees of aggregation, detail, and behavioral inclusion along a spectrum. For example, IO tables can be understood as weighted, directed networks of the inter-industry market on the sector level, and integrating dynamics or assessing structural properties with IOs is strongly tied to network approaches.[154] The approaches are not optimization based and allow for the assessment of structural properties and emergence, such as cascading risk. IOs are frequently employed for short-time quantification of disaster impact through sector dependencies[128] but are limited by high aggregation,[155] while networks generally allow for more detail, such as focusing on a specific supply chain.[156] Such structural assessments have been used to explore cascading loss and risk amplification in the GFS, e.g., estimating the impacts of production shock and trade disruptions in international trade networks between countries.[30,85,157] While analysis of the supply chain at firm level offers more meaningful results,[89] challenges in acquiring global supply chain data currently restrict studies to country-scale[152] or specific goods.[156,158] Those representations share that they do not represent individual actor behavior, preferences, and power dynamics. However, these aspects can be incorporated to allow for further exploration of systemic risk, as in multi-layer behavioral networks. These can integrate micro-, meso-, and macro-levels of analysis, heterogeneous spatial and temporal preferences, asymmetric information transmission, and path dependence while maintaining stock-flow consistency.[145] Behavioral networks are an example of ABMs, explicitly incorporating structural properties of the system. As system dynamics arise from actor preferences, behavior, and interactions, ABMs can be used to discover possible policy-relevant scenarios arising from self-organization within the system.[159,160] Furthermore, they can incorporate learning, complex adaptation, and diffusion dynamics.[144] High computational costs, calibration issues, and data availability impose limitations on ABMs.[144] However, recent advances in those areas have improved the ability to forecast short-term impacts of systemic shocks, as demonstrated in the economic context with the COVID-19 pandemic.[161] Similar approaches have been suggested to assess resilience and risk in the GFS.[162]

System dynamics models (SDs) represent feedback and delays by tracking the changes of physical or non-physical stocks and flows over time.[163,164] Explicitly capturing the evolution of the system while including interactions, relationships, as well as bounded rationality of actors,[165] SDs are well suited to study emergent behavior, e.g., self-evolution, and cascading effects.[166,167] However, system behavior is usually captured at a more aggregated level,[165] as in the FELIX model,[168] limiting representation of agent heterogeneity and spatial dimension, as well as structural properties and hierarchy.[169] To overcome these limitations, SDs may be coupled with other model types such as ABMs.[169] Similarly, SDs may be incorporated into IAMs to capture feedback with the socio-economic environment and may be used for participatory modeling and stakeholder engagement.[169]

Large models, including all dimensions and functions of the GFS, have the strength of capturing interactions and feedback more broadly and comprehensively. However, such complicated models come with drawbacks, as it is nearly impossible to explore the full parameter space, and they bear the risk of overfitting, with implications for the explorable solution space as well as decision-making.[28] Furthermore, richer models capturing the system in greater detail might not necessarily lead to better predictions.[123] Hence, it is not the aim of the criteria to advocate for the sole use of complicated models encompassing all aspects of the GFS and its complexity. In contrast, simpler or stylized models may be employed for the exploration of general properties associated with increased risk of cascading impacts.[145,170] Simplified and modular approaches may offer better understandability and may be used to inform or be expanded into larger-scale or more detailed models, which might be useful for integrating dynamics on smaller scales or for specific commodities. In these cases, the criteria may be used to identify and communicate aspects not included in the model, to assess potential limitations and associated consequences for the derived results.

While assessment with the criteria aids in uncovering general methodological assumptions, strengths, and weaknesses for resilience and risk assessment, decisions on model suitability should be accompanied by a detailed and informed study of its individual specificities. This includes the identification of a sufficient degree of abstraction and aggregation for a given purpose, boundaries, relevant variables and processes, and the inclusion of an interdisciplinary and diverse set of stakeholders in the process. Since models inevitably reflect the worldviews and values of their creators, it's important to question their origins, intended purpose, and the potential impact of embedded values on their outcomes. While the criteria can help reveal underlying assumptions and serve as a starting point for identifying these values, they necessarily reflect the authors' perspectives and may be revised or expanded accordingly.

To accompany quantitative assessments of the future development of the GFS, approaches avoiding the need for explicit quantification, such as cross-impact balances, have been suggested.[171] Here, scenarios for future development are based on expert-based estimation of pairwise interactions between the most influential factors.[171] Other approaches actively involve stakeholders in scenario development to enable a broader understanding and visualization of dependencies to enable cooperation, as done in the FABLE Scenathons.[172] However, such approaches fundamentally depend on the opinions and relevant factors included, and it is hard to evaluate how these relate to reality.[136] Tools like robust decision-making may be employed to identify pathways most robust under uncertain futures.[173]

CONCLUSIONS

The GFS is an internationally interconnected, highly dependent complex system, currently unsustainable and insufficiently configured to absorb systemic risks. Building systemic resilience is limited by its complex dynamics, giving rise to unforeseen and undesired consequences. Models may play an important role in guiding policymakers to manage systemic risks. However, the suitability of existing policy assessment tools has not been evaluated so far. Capturing relevant characteristics of the GFS for resilience, the seven criteria—(1) aim to provide food sustainably, (2) scope and scale, (3) uncertainty, (4) structure and spatial heterogeneity, (5) actors and behavior, (6) emergent dynamics, and (7) non-food actors and systems—offer a structured approach to assess the suitability of existing approaches and highlight possible consequences of the neglect of key factors. Exemplifying their usage, the criteria are applied to assess frequently used quantitative models. Deterministic equilibrium- and optimization-based approaches, common for GFS analysis, are strongly limited by their underlying assumptions and structure. Models more closely related to systems dynamics and complex systems theory, such as networks, ABMs, or systems dynamics models, have an improved ability to capture risk or resilient behavior. However, they are not yet available at the required scale.

As existing models of the GFS are not sufficiently equipped to quantify or simulate its behavior under systemic risk, we are currently ill-equipped to assess the emergence and manage systemic risks within the GFS, with potentially dramatic consequences for global food security. New models that adequately incorporate networked properties, actors, and the complex behavior arising from their interactions are needed. Until such models become available, results derived from existing models should be handled with great care. They may be assessed with the criteria to communicate the limitations and implications of model outputs, thereby enhancing transparency and reliability. Based on these evaluations, simulations from models with complementary strengths may be compared to explore the space of possible outcomes. Furthermore, stylized models may be used to supplement the analysis and strategies, such as robust decision-making, and may be employed to decrease reliance on specific projections. However, unavoidable inherent limitations to our understanding of the complex behavior of the GFS, and hence its resilience, necessitate resilience-building efforts that reduce shock likelihood guided by the precautionary principle.

ACKNOWLEDGMENTS

We sincerely thank the reviewers for their feedback, which has greatly improved the paper. A huge thank you to Yekatherina Bobrova for her extensive time and effort in providing feedback on the framework, the resilience definition, and the graphics. Furthermore, thanks to Matthias Wildemeersch for his feedback on the manuscript and John Ingram for enlightening discussions about framing systemic resilience. We thank ClimateWorks for making this research possible by supporting E.P. with a Doctoral Scholarship.

AUTHOR CONTRIBUTIONS

E.P. conceptualized the framework, developed the methodology, did the formal analysis and visualization, and wrote the paper. M.O. and N.R. provided supervision and helped with review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used generative AI exclusively to enhance the vocabulary and shorten 10% of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2025.101460.

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