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Models of Future Food Systems Should Address Transformation Complexity and Uncertainty

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ABSTRACT

Food systems face increasing, multi-dimensional pressures that demand fully integrated assessments of environmental, social, health, nutritional, and economic dimensions to inform their transformation. Food system models traditionally designed for market-driven optimisation and economic efficiency may not be well suited to address these emerging needs, limiting their ability to support decisions and participatory processes effectively. Here we evaluate the extent to which current models represent food system transformations and identify challenges and opportunities in relation to key aspects of transformative change, including the representation of socio-political dynamics and human-nature feedbacks, links between global and local scales, robustness under uncertainty, and flexibility to evolving stakeholder needs. Based on an evaluation of current food system models, we identify ways forward to enhance the potential usefulness of modelling tools. Key research priorities include rethinking how models are *designed,* emphasising modularity and a diversification of models, as well as rethinking how models are *used,* suggesting their more effective integration into social and decision-making processes. Enhancing the utility of food system models is expected to prioritise and guide the practical activities involved in transforming food systems.

1. INTRODUCTION

Food systems are deeply interconnected with climate change, environmental sustainability, and broader societal systems, resulting in contested sustainability outcomes and highlighting the urgent need for transformative changes (*2, 3*). Understanding the complex, multi-decadal impacts of current food systems and transforming them towards preferred future systems that ensure food safety, security, and economic prosperity while improving public health and environmental sustainability is critical and challenging (*4*). It involves analyses that consider diverse technological and policy options in the long-term future (*5*).

Models are potentially useful tools in food system analysis (*6*), and have been used to serve scientific purposes including (but not limited to) evaluating agricultural mitigation strategies (*7*), designing sustainable land management practices (*8*), informing healthy diets (*9*), assessing impacts on natural capitals (*10*), and evaluating economic risks in agriculture (*11*). Some food system models have been specifically designed to inform policy decisions, particularly in Europe, where they play a role in impact assessments, including in regular reforms of the Common Agricultural Policy (*12*). Recent applications in policy evaluation include the EU Waste Directive Amendments (*13*), the EU 2030 Climate Target Plan and Biofuel Mandates (*14*), and the US Environmental Protection Agency's Renewable Fuel Standards (*15*). Their usefulness is underpinned by their ability to analyse possible systemic interactions, to provide insights into the complex sustainability impacts of current and future food systems. Food system models are diverse in scope and methodology (*6, 16, 17*). This paper defines them as formal analytical frameworks that represent multi-sector dynamics (*18*) by assessing the development of interconnected sectors across value chains. This ranges from focused analyses of food, land, and agriculture (*19*) to broader assessments of human-environmental interactions, including food and agriculture interactions with land, economy, water, and energy systems (*20*).

Food system transformations are inherently complex and uncertain, which must be addressed by models to meaningfully inform researchers and stakeholders. By transformation we mean a fundamental reorganisation of the way things are done to cope with drivers of change beyond the capacity of existing systems to adapt to (*21*). Moreover, food systems are characterised by greater diversity compared to other systems like energy, encompassing highly interconnected global value chains and diverse local and indigenous food systems, with often atomistic stakeholders, such as small and large-scale farmers, firms of different sizes in the food industry, specialised food stores and supermarket chains, NGOs, and consumers. This complexity means that food system transformations are challenged by information asymmetry and contested goals that need to be reflected in food system models. Transformations are also driven by interlinked technological changes and political, cultural, and societal shifts. This creates winners and losers which can provoke institutional and social lock-ins. Modelled transformation pathways might not accurately reflect the resulting barriers which challenge their feasibility (*22, 23*). Moreover, the long-term, multi-decadal nature of food system transformations, conditioned by the information asymmetries, makes food system transformation a highly dynamic and deeply uncertain process. These uncertainties, often falling under the categories of Knightian/Keynesian, deep, or severe uncertainty, challenge the inferences drawn from models for long-term decision-making (*24-27*).

Food system models vary in their ability to address the complexity and uncertainty of transformative change, depending on their modelling approach and structure, boundary conditions, scenario assumptions, and output metrics. For example, while progress has been made in modelling social heterogeneity and behavioural changes on the demand side, modelling dynamics in producers' behaviour remains challenging, such as farmers' adoption to climate change (*28, 29*). Similarly, uncertainty of food system transformations has been addressed by different scenario types and modelling approaches (*30*). Common approaches include sensitivity analyses (*31*) or evaluating pre-specified scenarios (*32*). However, it is still uncommon to capture broad system uncertainties with unknown probabilities (*33*) or to model uncertainties endogenously within the assumptions used to build model structures, such as farmers' expectations of changing agricultural policies or unpredictable droughts and how they adapt their practices accordingly (*17, 34*).

Models by nature focus on processes and result in metrics that are more easily simulated but that risk under-representing harder-to-formalise aspects due to limited data availability, missing empirical parameters, and methodological or computational challenges. This can provoke a disproportionate focus on some aspects, leaving out important real-world challenges or resulting in oversimplification, jointly creating cognitive biases in understanding food system transformations. These biases could make food system stakeholders to develop an illusion of analytical certainty or cherry-pick specific models or model results to support their own agenda.

Despite these concerns, models that sufficiently address complexity and uncertainty and can be effectively embedded in social processes that support decision-making can offer valuable insights that result in practical steps towards preferred future food systems. Given their potential role, it is imperative to identify model limitations in representing food system transformations and explore opportunities to improve them. Existing reviews have examined specific aspects of modelling such as their role in decision-making (*35*), scenario analysis (*30*), and governance (*16*). However, the extent to which these models capture the dynamics of transformative change in food systems remains underexplored. This leaves a gap in understanding the strengths, weaknesses, and emerging developments in modelling practices for food system transformations, which this paper aims to address.

Here we evaluate the extent to which current models capture food system transformations, highlight the challenges they face, and explore evolving approaches that can empower food system stakeholders to manage complexity in a dynamic and uncertain futures. While past studies have discussed the technical details of these modelling capabilities, we focus here on how these capabilities work together to address various aspects of transformation, and the resulting ability of different types of models to be embedded in social processes capable of supporting decision-making.

Among various approaches to food system modelling, we start by evaluating 20 models that represent different types of economic (partial and general equilibrium), integrated assessment, and coupled modelling (Sections 2 and 3). These types, while not representing or being mutually exclusive of other modelling approaches (e.g., process-based biophysical, multi-agent, econometrics), are widely recognised as commonly-applied types of models for food system analysis. They integrate micro- and macro-economic theory with social and natural system constraints, provide broad coverage of value chains (from production to consumption), enable cross-sectoral analysis, and play a key role in scenario frameworks that link to other research areas like climate and sustainability (*16, 17*). The evaluation of current models leads to identification of four challenges and four improvement opportunities that could push the boundaries of the current food system models, supported by case studies that we have conducted in recent years to illustrate their implementation (Sections 4 and 5). We then summarise these findings and call for diversifying array of models using different analytical approaches to better address complexity and uncertainty (Section 6). This can help in paving the way for food system models' further contribution to decision-making under uncertainty in high-impact international science-policy arenas as well as national and local decision-making.

2. METHOD

2.1. Selecting Models

Food system models in the context of this paper are computational tools used to simulate and analyse the interactions within and between food and other human-natural systems, such as agriculture, land, health, energy, and the broader economy. These models are designed to capture the complexities of food production, distribution and consumption, as well as their economic, health, and environmental impacts.

There is a vast body of literature that explains how these models evolved and function in food and agriculture (*16, 17, 36*) as well as in relation to food, land, and agriculture interactions with other systems in an integrated sustainability context (*37-39*). Key elements typically included in these models are land-use, crop and livestock production, trade, food demand, and costs of production. They integrate data from various sources to quantitatively estimate the supply, demand, and price of different agricultural commodities and to calculate their economic, health, and environmental impacts, using different methodological approaches (*36, 40*). The models are used to develop projections and explore impacts of changes in exogenous variables, or shocks, such as income and demography, policy, preferences or technology, and can thus also inform decisions for transformation to more sustainable food systems.

To provide an overview of key features and capabilities, we selected an illustrative set of models. We implemented a structured process similar to a systematic search with clear exclusion and inclusion criteria. This approach was designed to specifically focus on the most commonly used (rather than all, as a systematic review would have done) modelling framework and important published studies that used these models in the last two decades. We selected models based on three general inclusion/exclusion criteria:

- *Food and agriculture focus:* We prioritised models with a focus on the food system, excluding broader economic, energy, or climate mitigation models with only indirect links to food systems.
- *Commonly applied approaches:* We focused on frequently applied economic modelling approaches, that is partial and general equilibrium, integrated assessment models, as well as their coupled applications. We excluded approaches that, so far, have been less frequently applied to assess global food system transformations, such as statistical analysis (*41*) or purely biophysical process-based models (*42, 43*), or those considered niche or emerging, such as models of physical trade flows (*44*), multi-objective optimisation (*45, 46*), machine learning (*47*), and agent-based models (*48*). Some of these emerging approaches will be discussed later as opportunities in Section 4.
- *Relevance across geographical contexts:* We only included models with global or regional scope, as they are more widely known, and produce insights relevant across various contexts and regions. Several models at national and subnational scales are not explicitly covered in this section, but some are briefly mentioned later in Section 4.

The model selection initially relied on published studies suggested by four key modelling review papers on food system models in recent years (*16, 30, 40, 49*). This resulting list of models was then expanded with additional studies through backward snowballing, in which a reference list is used to identify new sources, and forward snowballing, in which additional sources are identified based on those cited by our initial list. We further triangulated this list with food system studies using models in the context of the Agricultural Model Intercomparison and Improvement Project (AgMIP) (*36*), and models listed by the Integrated Assessment Modelling Consortium (IAMC). Some of these studies used the same model to address different questions, others used different models with similar approach, boundary, and level of detail, and some used multiple models differing more substantially for intercomparison.

This iterative process identified 20 food system models (Appendix A) used frequently in the literature, across 150 published studies that provide sufficient technical and application information to enable their assessment (Appendix B). These 20 models were categorised under partial equilibrium, general equilibrium, and integrated assessment models, as well as the coupling of models from these three types that are frequently used in the food system transformation context.

Commonly used partial equilibrium models include AgLINK-COSIMO (*50*), CAPRI (*51*), GLOBIOM (*52*), IMPACT (*53*), MAgPIE (*54*), and SIMPLE-G (*55*). These are economic models specifically developed to examine food, agriculture, and land use change (*56*). The second type includes general equilibrium models, which are also economic models for simulating economy-wide impacts of policies and shocks, such as AIM (*57*), CGEBox (*58*), DART-BIO (*59*), GTAP (*60*), GTEM (*61*), MAGNET (*62*), and MIRAGRODEP (*63*). A third type includes standalone integrated assessment models, which are simplified representations of physical and social systems, focusing on the interaction between economy, society, and the environment, such as GCAM (*64*) and IMAGE (*65*). These primary types serve as umbrella terms that encompass a variety of models in terms of solution method (simulation vs. optimisation), incorporation of climate impacts (endogenous vs. exogenous), spatial and temporal dimensions, interventions considered (supply vs. demand), and number of food commodities included (*38*). We also considered the coupling of models from these types as different types of models mentioned above can be coupled to form integrated assessment models, for example, Globe-IMPACT (*66*), LandSyMM (*67*), MAGNET-IMAGE (*68*), MESSAGEix-GLOBIOM (*69*), and REMIND-MagPIE (*70*). A full list of these models, their full names, description, and sources are provided in Appendix A.

The list of selected models is not exhaustive nor intended to show the entire literature. For example, process-based (*43*), statistical (*71*), and multi-agent (*29*) models are not included in this section. There were also other models under the selected types of economic (partial and general equilibrium), integrated assessment, and coupled modelling which we did not study. Rather, the purpose of the paper is to select and evaluate in detail a few exemplary, commonly used models for food system analysis, with a view to assessing whether this institutionalised dependence remains warranted as new approaches evolve. Readers can refer to Teeuwen *et al.* (*16*) for a more systematic model typology and this paper's Appendix C where we provided a list of some of these other models for interested readers.

2.2. Evaluating Model Capabilities

We evaluated the extent to which selected models can address three key dimensions of food system transformations, each of which have multiple sub-dimensions (italicised here): sustainability outcomes, drivers of change, and value chains. These dimensions reflect the need to understand transformation as responses to systemic drivers of change that are beyond the capacity of current food systems to adapt, and the need to redirect food system activities toward preferred outcomes across multiple spatial and temporal scales (*5, 21, 72*). These outcomes can include *food security and nutrition*, *social welfare*, *economic prosperity*, and *environmental sustainability*. Various drivers of change flow through entire value chains, from *production*, to *distribution*, *processing*, *consumption*, and *waste*. Key drivers can be i*nnovative interventions* (e.g., technology and practice change, novel proteins for food) (*73*), *techno-economic drivers* (e.g., innovation, economies of scale, maturation of technologies), *biophysical* drivers (e.g., land-use change, climate change impacts), *socio-economic* drivers (e.g., demographical change, taxes, subsidies, regulation), and *political-institutional drivers* (e.g., vested interests and coalitions of powerful actors) (*23*). These dimensions together represent the multifaceted nature of food system transformation which we used to evaluate the selected models (see Table D1 in Appendix D for dimension definitions).

Two primary co-authors initially analysed published studies (i.e., papers in Appendix B) related to the selected models and assigned one of four levels of inclusion for each dimension assessed, based on the authors' interpretation. These levels align with a framework previously applied by the IPCC for the qualitative assessment of modelling frameworks in the context of climate change mitigation (*74, 75*):

- *Endogenous-explicit:* The dimension is directly simulated within the model through an explicit representation.
- *Endogenous-implicit:* The dimension is directly simulated within the model using a proxy (e.g., average food affordability estimated through changing food prices).
- *Exogenous-explicit:* The dimension is modelled as an external driver rather than simulated, but is explicitly represented.

- *Exogenous-implicit:* The dimension is modelled as an external driver rather than simulated and is indirectly represented through a proxy (e.g., a reduction in food demand as a proxy for reducing food loss and waste).

We did not consider a dimension to be endogenous when it was simulated through loosely coupled models, for instance a health model that uses the outputs a food system model as inputs, but we acknowledged these relevant applications in Appendix Table D2. In several cases, models can simulate a dimension both endogenously and exogenously, for instance carbon price within the agrifood and climate policy dimension. In such situations, we classified the dimension as endogenous.

For any dimension not included in a model or for which insufficient information was available, the "not included or insufficient information" classification was applied. In our study, the assignment of these levels was grounded in how the selected models were used in the context of the published studies analysed (i.e., papers in Appendix B), rather than their broader potential capabilities or future development. The co-authors provided justifications for the assigned levels, referencing relevant studies as evidence (see Table D2 in Appendix D for detailed evaluations). To minimise bias in the evaluation, all co-authors reviewed the assigned levels and flagged those parts that could be assessed differently, for further deliberation and modification. We acknowledge that these models are continuously evolving, with several dimensions potentially under development or already implemented but not yet published. We also recognise that coupled models have the potential to cover a greater scope of dimensions of the food system at once compared to individual models.

2.3. Identifying challenges and opportunities

The evaluation of selected models highlighted key limitations and gaps in their representation of food system transformation, which varied across models depending on their levels of complexity and modelling capabilities. We focused on gaps and those aspects that were underdeveloped, to identify and discuss critical challenges. To address these challenges, we drew on best practices and alternative approaches introduced in the broader literature or used in modelling case studies by co-authors in recent years, beyond standard general and partial equilibrium, integrated assessment, and coupled modelling, to suggest potential opportunities and areas for future improvement. These included alternative approaches from diverse disciplines, such as agent-based modelling, participatory systems modelling, and statistical surrogate modelling. When discussing these alternative approaches as opportunities, we emphasised their potential applications and critically examined their constraints, grounding in both published critiques and the co-authors' previous experiences. This balanced perspective ensures that these approaches are not introduced as tools with specific strengths and constraints.

3. STATE OF THE ART

Food system models evaluated vary in their design, each having different boundaries and details, resulting in different levels of model complexities and diverse modelling capabilities. Recognising these distinctions, this overview focuses on their broader strengths and limitations across sustainability outcomes, drivers of change, and value chains (Table 1), providing a foundation through which we will explore the challenges and opportunities in the rest of the paper.

In representing diverse drivers of change (Table 1), most models evaluated account for a broad range of exogenous drivers regarding technology and policies, including drivers of productivity improvement and food waste reduction (*76*). However, the real-world effectiveness of these drivers depends heavily on behavioural responses to them, such as the adoption and diffusion of these technological innovations (*77*) and the implementation of adequate policy support. These socio-political-institutional drivers are broadly absent or under-represented in most of the models evaluated. Partial and general equilibrium models, for instance, often rely on assumptions of perfect markets and economically optimal decision-making. While some studies have attempted to integrate cultural factors into the parameterisation of food system models (*78*), a more comprehensive and general representation of culture as driver of transformation is missing. Among the models reviewed, partial equilibrium models are also more limited than other multi-sectoral (general equilibrium and integrated assessment) models in their ability to evaluate feedbacks between food system transformation and other sectors of the economy. Together these limit the capability of most models evaluated for endogenously representing socio-political drivers and human feedback interactions, which can significantly influence food demand and play a critical role in the sustainability transformation of food systems through change in lifestyle and diet. As a result, these are often represented in scenarios quantified as exogenous assumptions like the shared socioeconomic pathways. We will further explain these challenges around the modelling of socio-political drivers and human feedbacks in Section 4.1.

In terms of sustainability outcomes (Table 1), most models evaluated have predominantly focused on sustainability outcomes related to production, such as greenhouse gas emissions, land use, and economic output. This emphasis is largely driven by modelling demand and policy priorities, particularly in areas where there has been more demand for robust quantification, such as emission accounting and agricultural productivity assessments. Since important environmental impacts originate at the production stage, there has been greater investment in models designed to capture these effects, reinforcing perhaps a production-centric bias. However, this bias has led to underrepresentation of the broader food system in these models, particularly post-production processes such as food distribution, processing, retail, and heterogeneity of consumers. As a result, critical sustainability dimensions such as dietary health impacts and nutrition are often underrepresented. While some models have expanded to incorporate these elements, they remain fragmented and secondary to production-oriented analyses. Among the models reviewed, general equilibrium models are built to model economies rather than food systems, which means they include aggregated representations of agricultural production and consequently aggregated projections of sustainability outcomes. Recent developments in the databases used by some general equilibrium models have led to an improved, more nuanced representation of land use (*79*), nutrient accounting (*80*), irrigation water use (*81*), trade (*82*), and agri-food commodities (*83*). These advancements now enable general equilibrium models to offer more detailed environmental and health impacts of the food system. However, all models reviewed are constrained by a certain level of spatial aggregation which highlights the trade-offs between model applicability across different regions of the world and the limited representation of local environmental, socio-economic, and cultural characteristics of food systems. Moreover, while these models can explore equity, or lack thereof, in food system transformation across broad world regions (*84*), they are often more constrained in their ability to assess sub-national and household-level variations in food affordability and undernourishment. This limits their ability to analyse social heterogeneity and multi-scale processes. We will further unpack this challenge in Section 4.2.

Value chains play a crucial role in shaping food system dynamics. Most of the evaluated models are dynamic, incorporating supply and demand over time, and can analyse competing demands for food, feed, fibre, and bioenergy. They also tend to focus heavily on international trade and supply-demand balance. Among models evaluated, general equilibrium models offer a more global value-chain perspective by capturing some of the key economy-wide impacts of food system changes (*85*). While these models simulate trade dynamics and interconnected agricultural markets, they are often limited in representing the extent to which countries are sensitive to both domestic and external demand fluctuations. This includes their ability to assess supply chain resilience in the face of acute shocks, such as extreme weather events, which is particularly critical for economies reliant on agri-food imports to meet demand or on exports as a key revenue source. Current models also often work under the assumption that risks are predictable and can be addressed by assigning probabilities to clearly defined events. This approach has contributed to a reliance on Bernoullian utility theory (i.e., the idea that people consider both the possible gains and losses of an action, as well as the utility they'll receive from it (*86*)). While useful in many contexts, such assumption can limit the ability to fully account for the complexities and uncertainties inherent in dynamic and evolving food systems. Together, these limit the extent to which uncertainty across value chains can be explored with these models (see further discussion in Section 4.3). Underrepresenting uncertainties can increase reliance on pre-specified scenario assumptions.

While coupled models provide broader coverage of food system transformation dimensions, they tend to be less flexible or include less details than individual models. Achieving consistency between models often requires additional model development efforts, as well as iterative simulations to achieve satisfactory convergence in results (e.g., REMIND-MAgPIE (*70*)). Alternatively, some coupling frameworks rely on emulator models, which may simplify underlying dynamics of the system (e.g., MESSAGEix-GLOBIOM (*69*)). These limitations ultimately constrain the ability of such models to effectively support decision-making in rapidly evolving policy and market landscapes (see further discussion in Section 4.4).

The evaluation of food system models across sustainability outcomes, drivers of change, and value chains highlighted key challenges related to both complexity and uncertainty. These included limited representation of socio-political drivers, human-nature feedbacks, social heterogeneity, and multi-scale processes (complexity-related issues) as well as difficulties in addressing uncertainty and adapting to evolving stakeholder needs in dynamic contexts (uncertainty-related issues). Addressing these challenges requires innovative approaches to food system modelling. We unpack and further discuss these challenges as well as innovative approaches that currently exist to address them in the next section.

Table 1. Overview of the ability of each model to represent various dimensions at different levels of inclusion: explicitly or implicitly, endogenously or exogenously. Levels of inclusion were assigned by co-authors based on a review of selected published studies for these models. Appendices A and B provide the detailed and extended list of selected food system modelling studies reviewed for this evaluation. Tables D1 and D2 in Appendix D provide definition of the dimensions and justification/references in support of the assessment provided in each cell, respectively. PE is partial equilibrium, GE is general equilibrium, and IAM is integrated assessment model. This table is for illustrative purposes to identify challenges and does not provide a comprehensive review of all modelling work in the literature.

Legend:

	Endogenous	Exogenous
Explicit	A	B
Implicit	C	D
Not included or insufficient information	E	E

Dimensions			PE						CGE							IAM		Coupled models				
			AgLINK-COSIMO	CAPRI	GLOBIOM	IMPACT	MAgPIE	SIMPLE-G	AIM	CGEBox	DART-BIO	GTAP	GTEM	MAGNET	MIRAGRODEP	GCAM	IMAGE	GLOBE-IMPACT	LandSyMM	IMAGE-MAGNET	MESSAGEix-GLOBIOM	REMIND-MAgPIE
Sustainability outcomes	Food security and nutrition	Health impacts of diets	E	E	E	A	A	E	E	E	E	E	E	E	E	E	E	A	E	E	E	A
		Average food affordability	A	C	C	C	C	C	A	C	C	A	E	A	A	C	E	A	A	A	A	A
		Undernourishment	A	E	A	A	A	E	A	E	C	A	E	A	A	A	A	A	A	A	A	A
	Social welfare	Employment	E	E	E	E	A	E	A	A	A	A	A	A	A	B	E	A	E	A	A	A
	Economic prosperity	Trade	A	A	A	A	A	A	A	A	A	A	A	A	A	A	E	A	A	A	A	A
		Economic return	A	A	A	A	C	A	A	A	A	A	A	A	A	A	E	A	E	A	A	A
	Environmental sustainability	Emissions	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
		Biodiversity loss	E	E	A	E	A	E	A	E	A	E	E	E	E	E	A	E	A	A	A	A
		Water resource use	E	A	A	A	A	A	E	A	E	A	E	E	E	A	A	A	A	A	A	A
		Biogeochemical flows	A	A	A	A	A	A	E	E	E	E	E	E	E	A	A	A	A	A	A	A

Drivers of change	Interventions	Technology/practice (AFOLU measures)	A	A	A	A	A	A	A	E	E	A	E	A	E	A	B	A	E	A	A	A
	Socio-economic drivers	Demographics	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
		GDP	B	B	B	B	B	B	A	A	A	A	A	A	A	A	B	A	B	A	A	A
		Food demand	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	A	A	A	A	A
		Agrifood and climate policies	B	A	B	B	B	B	A	A	A	A	A	A	A	A	B	A	A	A	A	A
	Biophysical drivers	Land-use change	A	A	A	A	A	A	A	A	A	A	E	E	A	A	A	A	A	A	A	A
		Bioenergy supply	A	A	A	A	A	A	A	B	A	A	E	A	A	A	A	A	B	A	A	A
		Chronic climate change impacts	B	B	B	B	B	B	B	B	E	B	B	B	E	B	B	B	A	A	A	A
		Acute shocks	B	E	E	B	E	E	B	E	E	B	E	B	B	B	E	B	E	B	E	E
	Techno-economic drivers	Maturation of technology/innovation	B	B	B	B	B	B	C	E	E	C	C	C	E	C	C	B	C	C	B	B
	Political-institutional drivers	Vested interests and coalitions	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Value chains	Production	Primary production	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
		Aquaculture and fisheries commodities	A	A	D	E	E	E	E	A	A	A	E	A	A	E	E	E	E	A	D	E
	Distribution	Domestic transport and storage	E	C	E	E	A	B	E	D	D	D	D	D	D	A	E	E	E	E	E	E
	Processing	Processed food commodities	A	A	A	A	E	C	A	A	A	A	A	A	A	E	E	A	E	A	A	A
	Consumption	Demand shift	B	B	B	B	B	E	B	B	B	B	E	B	B	B	E	B	B	B	B	B
		Novel food and feed	E	B	B	E	B	E	E	E	E	E	E	A	E	E	E	E	E	A	B	B
	Waste	Food loss and waste	B	B	B	B	B	B	B	B	E	B	E	B	B	D	E	B	D	B	B	B

4. CHALLENGES AND OPPORTUNITIES

4.1. Socio-Political Drivers and Human-Nature Feedbacks

Globally, food systems have been driven over decades mostly by technological advancements and assessed according to economic goals such as the value of production and exports. Technology has spread through global and national market integration, partially fostered by policy reforms. These processes are relatively well represented in existing (mostly partial and general equilibrium) economic food system models, which have been in common use for several decades. They have therefore dominated the understanding of food system change, emphasising market mechanisms, supply-chain interactions, and more recently biogeochemical processes impacting environmental footprints. Key socio-political drivers, such as changes in consumer preferences and policies including taxes, subsidies and regulation, are mainly exogenous to these models and addressed by scenario analysis. However, these drivers themselves depend on the food system, and their feedback interactions can be also endogenously represented in models, for instance, how food system impacts on the environment, animal welfare, import dependency, and nutrition and public health can shift preferences and drive policy change. Equally, models cannot, or only very partially, capture impacts on broader human health, well-being, equity, and social justice (*87, 88*). These omissions have led to a preference for evaluating technology and policy options with clearly defined market impacts, a focus on economic outcomes, and selected environmental impacts that directly threaten those economic outcomes. It has also resulted in the underrepresentation of Indigenous food systems and knowledge from these models (e.g., traditional food crop cultivation, indigenous knowledge of food processing and preservation), overlooking their critical contributions to sustainable and resilient food practices (*89*), as well as their role in addressing equity and social justice in food systems (*90*).

For example, model-based scenarios have been crucial in establishing the GHG mitigation potential of dietary changes and their impacts on land-use, fertiliser consumption, and ecological restoration (*91-95*). Yet, analysis often draws on stylised (and sometimes unlikely) assumptions such as a homogenous global shift to flexitarian or Mediterranean diets, largely overlooking the complex cultural, social, and lifestyle factors influencing dietary behaviour (*96, 97*). They also often base their projections on modern contemporary diets, underrepresenting the traditional plant-based dietary diversity of Indigenous communities, which has been recognised for its significant health and nutritional benefits (*98*). While simplified assumptions are sometimes unavoidable for practical data and modelling requirements, they run the risk of undermining the plausibility and feasibility of policy recommendations (*99, 100*).

Current approaches to economic modelling rarely consider human risk behaviours adequately in the way they explicitly model decision-making. Empirical studies have repeatedly shown that human behaviour is more complex and diverse (*101*), constrained by what we can practically know at any one time, and deviates significantly from, for instance, expected utility theory (*102, 103*). Some modelling efforts have explored the effects of these deviations, such as incorporating degrowth principles and equitable wealth distribution in Bodirsky *et al.* (*71*). These adjustments however are typically introduced exogenously as scenarios rather than being integrated directly into decision makers' objective functions. Understanding human feedback is important for identifying promising demand-side levers for accelerating food system transformation, and policy levers to reinforce dynamics such as social contagion feedback that promote the spread of new behaviours and can move systems rapidly into a new state (*104, 105*).

Incorporating these social and political dynamics into integrated food system models requires more specific models that can sufficiently represent socio-political dynamics without becoming overly complex or all-encompassing, for example modelling transformation via coupling with other models. Modelling approaches, such as agent-based and system dynamics models among others (e.g., models of social innovation diffusion (*106*)), can offer valuable tools for integrating socio-political factors. Agent-based models can simulate diverse behaviours and decision-making across actors and scales (e.g., alternative land management strategies (*35*)), while system dynamics model aggregate interactions within human-natural systems (e.g., interactions between climate health risk perception and dietary shifts in Model Snapshot 1 (*107*)). That said, it is important to also recognise that some of these models may have challenges when scaling up to national and global levels, which could limit their practical applicability. For example, agent-based models can face computational constraints when applied to a large population while system dynamics models, due to their high level of aggregation, may oversimplify sectoral heterogeneities when operating at broader scales. While these alternative modelling approaches can offer valuable insights into potential food system processes and dynamics, their integration into food system analysis also requires careful consideration. Ensuring empirical grounding and addressing scalability issues are critical steps to enhance their relevance and reliability. Attention is also needed to ensure models are sufficiently transparent to provide confidence in their result to decision makers.

Integrating insights from diverse disciplines and practice into food system models can also enhance models' relevance to socio-political and human factors. For example, the role of policy beyond taxes and subsidies in shaping the policy context is often underrepresented in food system models. Empirical studies related to policy, such as Wuepper *et al.* (*108*), are emerging that can inform food system models, improving their relevance and accuracy in guiding policy and decision-making. In another example, behavioural economics offers insights into how farmers deviate from the standard rationality assumptions in land management (*109*). Psychology also offers insights into reciprocal interactions between personal and social drivers in dietary shifts (*110*), while political economy offers insights into how power relations shape stakeholder actions (*111*). Incorporating diverse ways of knowing (i.e., respectfully, collaboratively, ethically, and reciprocally) can also enhance our understanding of local ecosystems and better integrate Indigenous Peoples' knowledge systems, which are invaluable for promoting environmental sustainability (*112*). Empirical research on sustainability transitions and transformations has also generated insights and frameworks for understanding the social and political mechanisms driving transformative change including socio-political struggles between emerging innovation and established systems (*113*). Recent research has begun exploring opportunities to combine these more qualitative insights with quantitative modelling, such as in modelling lifestyle changes (*107*), circular economy options (*114*), and regenerative agriculture adoption (*115*).

Model Snapshot 1. Modelling human-earth system feedbacks to explore dietary shifts

FeliX is a globally aggregated, feedback-rich system dynamics model of climate, economy, environment, and society. It represents the main biophysical and socioeconomic mechanisms of global environmental and economic change within and between economy, energy, carbon cycle, climate, biodiversity, water, population, and land use systems (*116, 117*). The main purpose of the model is to support what-if analyses of cross-sectoral feedback, with less focus on techno-economic detail at a high-resolution level. The model has been used in a variety of cases, such as assessing the socioeconomic and environmental impacts of improving Earth observations (*118*), analysing alternative livestock feed sources as well as atmospheric and terrestrial carbon cycle impacts of global emission pathways (*119*), investigating sustainable development pathways based on an endogenous analysis of SDG synergies and trade-offs (*120*), and analysing the trade-offs between environmental pressures and poverty (*121*).

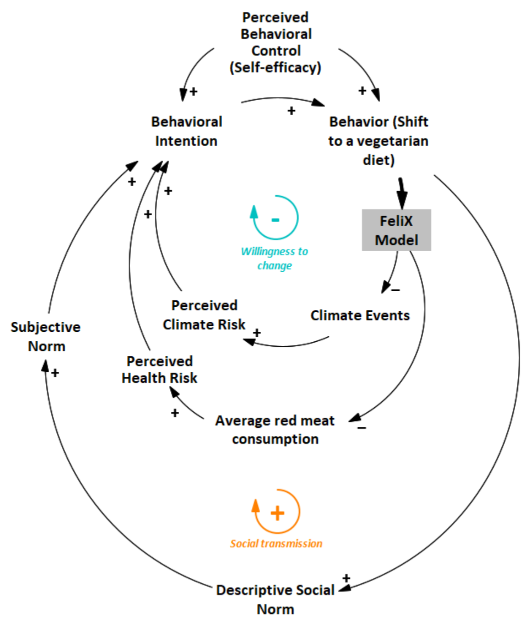


Figure 1. Main feedback mechanisms governing dietary shifts in the FeliX model

FeliX includes several cross-sectoral feedback interactions between biophysical and socioeconomic systems, such as the climate impacts of energy and land use emissions, the environmental impacts of water and fertiliser use, and the impacts of climate damage on economic growth, crop yields, and human mortality. Besides those, Eker *et al.* (*107*) extended the FeliX model to include behavioural factors, and the dietary shift dynamics resulting from the interaction of behavioural, social and environmental drivers.

Figure 1 depicts the two main feedback mechanisms in this extension. First, the social transmission loop describes how individuals change their intentions and eventual behaviour, i.e., by shifting to a vegetarian diet, according to social norms. The visibility of the new behaviour in the society influences the individual intentions in return. Second, an increase in perceived climate and health risks associated with red meat consumption stimulates further behaviour change towards low-carbon diets, and these population dynamics drive the food demand, GHG emissions and climate events through the existing modules of the FeliX model. Considering the uncertainties in quantification of this global model of human behaviour, Eker *et al.* (*107*) used it as a heuristic platform to run computational uncertainty analyses and reached two key conclusions: First, for harnessing the positive impacts of dietary changes on land use, carbon emissions and fertiliser consumption, a moderate consumption of animal products by a large population fraction is more important than a small population fraction abandoning animal products completely. Second, the social norm effects, especially among young adults, is the main factor accelerating widespread dietary shifts.

4.2. Social Heterogeneity and Multi-Scale Processes

Food systems span diverse socio-economic-ecological contexts, from primary production to industrial food manufacturing, and to nutrition and health via food distribution and retailing. Each of these is shaped by unique biophysical, socio-economic, and institutional factors (*122*). Given that effective transformations are multi-scale, efforts to model food system transformation should be able to incorporate spatial scales, diverse agents, and context-specific decision-making.

Among the models evaluated in Section 3, the availability of harmonised global statistics of countries (e.g., from FAOSTAT since 1949) underpins efforts to enhance a diversified representation of primary agriculture in partial equilibrium models like GLOBIOM, CAPRI, and IMPACT. Some models also incorporate sub-national data to better capture bio-physical factors (e.g., climate, soil, slope) that influence agricultural production and land use. For instance, some general equilibrium models use GTAP's Agro-Ecological Zones to disaggregate national land-use into global zones, while others, like CAPRI and CGEBox, rely on sub-national statistics for finer resolution. Gridded land-use data from satellite products, used in models like MAgPIE and GLOBIOM, have further enhanced spatial detail. To improve environmental impact representation, economic models have been also linked to bio-physical models operating at fine grid levels (*123*), with downscaling techniques like cellular automaton (*124*). Despite these efforts, representing sub-national technological and consumption differences remains challenging. GTAP's AEZ approach, for example, assumes uniform cost structures across zones within a country, while GLOBIOM and some other models often assume uniform yield gaps between potential and observed yields at national level.

Beyond spatial disaggregation, another challenge in economic models for food systems is representing agent heterogeneity and localised decision-making. Production, intermediate, and final household demand of agricultural products are mostly represented by aggregated agents in food system models, such as by one representative firm for each sector and one representative household in each model region in most global general equilibrium models. In order to avoid aggregation bias, in addition to using a higher spatial resolution, partial equilibrium models have sometimes partially dis-aggregated production decisions to more detailed representative farms by farm size and specialisation (*125-127*), for instance, to depict the impact of differentiated policy support schemes. In another example, while partial equilibrium models do not capture labour markets, general equilibrium models typically show limited dis-aggregation (for instance, gender differentiation is missing) and partly take simplified assumptions, such as full mobility, no wage rigidities, and other market imperfections.

These simplifications are sometimes unavoidable and are partly due to limited high-resolution socio-economic data, which makes it challenging to incorporate nuanced assumptions about the context, without introducing significant uncertainties. Sub-national (e.g., consumption) data is also often scarce, as harmonised global household surveys with regional, demographic, or income-based differentiation are rarely available. Consequently, while higher spatial resolution improves the representation of land-use changes and environmental impacts, it offers limited progress in capturing sub-national agricultural production systems or consumption patterns.

A multiscale modelling approach could address some of these limitations. For example, bio-economic farm models offer a more detailed representation of agricultural technologies compared to some existing food system models (*128*), but they often lack the ability to incorporate market feedback, which limits their scope. Recent advancements in surrogate modelling (*129*) present promising opportunities for coupling and integrating these models with other frameworks like agent-based models to better capture local and regional interactions among farms, such as the adoption and diffusion of new technologies (*130*). That said, the global application of these approaches is constrained by the limited availability of farm structure data and related statistics needed to inform and calibrate such models. Model coupling, particularly with global economic models, could allow spatially explicit models to focus on local contexts while global models capture broader dynamics, such as trade. For example, Johnson *et al.* (*131*) demonstrated the integration of local to global models to analyse economy-ecosystem interlinkages; an approach that could enhance food system transformation by capturing local diversity while maintaining coherence with global processes.

Another approach involves calibrating a global model with national statistics, policies and stakeholder inputs, producing nationally specific yet globally consistent outcomes. Examples of such initiatives to address global questions by tailoring models include the FABLE Scenathon (i.e., Scenario-Marathon) (*132*) and country-level calibrations of current global models such as GLOBIOM-China (*133*), GLOBIOM-Brazil (*134*), MAgPIE-China (*135*), and GCAM-USA (*136*) models.

Integrating local and indigenous knowledge through participatory and co-creation methods can help bridge the gap between generalised scientific models and diverse regional realities (*137, 138*). For example, at the sub-national level, participatory modelling approaches, such as those by Davis *et al.* (*139*) in South Africa, can reveal diverse stakeholder perspectives and local priorities, informing a more nuanced understanding of food system transformations. Participatory process can also capture regionally significant co-benefits and trade-offs. For instance, group model-building in Pakistan (*140*) and participatory systems modelling in Australia (*1*) identified multi-objective solutions to address priorities related to agricultural production, soil salinity, and water management (see Model Snapshot 2). Approaches like serious games, foresight, and scenario planning can also complement participatory modelling, helping actors envision and implement sustainable food systems within their local and regional context (*141-143*). Furthermore, incorporating Indigenous and First Nations knowledge into these participatory methods can highlight traditional practices, cultural values, and deep connections to the land, enabling more equitable and context-specific food system transformations (*144*). While these approaches show a great promise to better represent social heterogeneity and multi-scale processes, their successful implementation could be challenging and requires careful coordination, collaboration, and support to build the capacity to co-design and manage models and their interactions.

Model Snapshot 2. Actionable regional pathways for agriculture-economy-environment trade-offs

Spanning over 27,000 square kilometres along the southern bank of the River Murray in northern Victoria, the Goulburn-Murray Irrigation District (GMID) is the largest irrigation district in Australia and has a population of 170,000 people. The GMID supports extensive dryland and irrigated cropping, dairy production, and horticulture, generating a gross value of approximately $1.4 billion annually. However, the GMID is also facing significant challenges related to climate change, water availability, water price variability, commodity price volatility, skilled labour availability, and a declining population. These challenges make the GMID a unique and complex social-ecological system with many interacting elements that requires a transdisciplinary approach to develop locally-tailored pathways based on co-produced knowledge about the system.

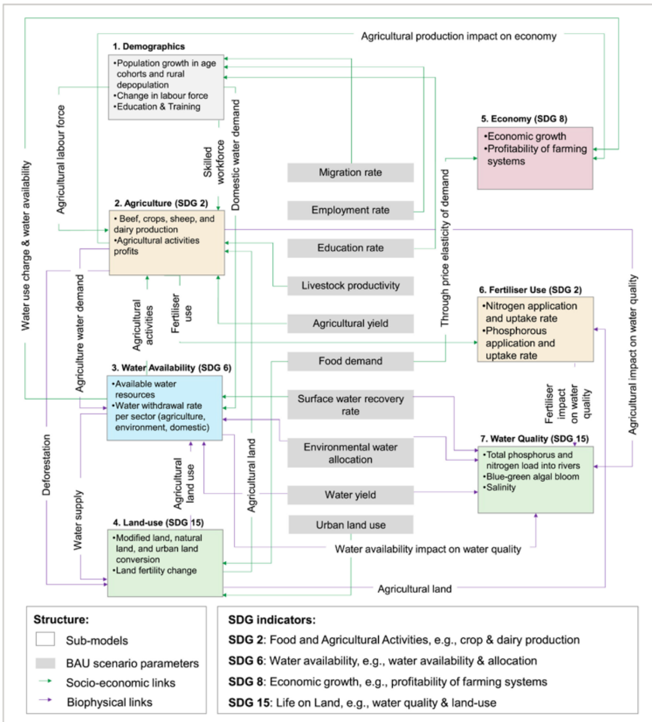


Figure 2. Participatory modelling for analysing interactions between agriculture and other sectors (*1*).

Using the UN Sustainable Development Goals as a framing and based on semi-structured interviews and desktop research, Bandari *et al.* (*145*) identified the five highest priority sustainability issues and their trade-offs in the GMID, with food and agriculture at the centre: SDG2 Zero Hunger, SDG6 Clean Water and Sanitation, SDG6 Decent Work and Economic Growth, SDG13 Climate Action, and SDG15 Life on Land. This system-level understanding was then formalised into a participatory system dynamics model developed in a co-design process, called the Local Environmental and Socio-Economic Model to analyse and quantify context-based SDG interactions at the local scale around food and agriculture (*1*) (Figure 2). Together with stakeholders, Bandari *et al.* (*146*) also assembled a list of potential pathways which could be implemented locally and used the model to assess their effectiveness for system change. These included a range of actions aimed at increasing agricultural productivity and resource use efficiency and re-use, reducing costs, and producing premium products.

4.3. Unpredictability and Knowledge Uncertainty

Food system transformations are ongoing and unpredictable processes, shaped by diverse forces such as technological advancements that reshape agricultural practices and changing consumer and political preferences that can influence patterns of food consumption and waste. These changes highlight the complex dynamics of agri-food systems, where outcomes are often deeply uncertain, possibly presenting both opportunities and challenges. Under these conditions of uncertainty, the role of models shifts from being simply computational tools that provide answers to decision-makers, to models being seen as a thinking aid to navigate complex and uncertain environments and one of many factors influencing the heuristics and practice of decision-making (*147*).

There are times that risk-based, statistical, and probabilistic approaches are appropriate to address well-understood (i.e., known knowns) aspects of the current food system such as understanding the nutritional benefits of diverse diets and the risks of over-reliance on processed foods (*148*). However, even in areas that appear to be well-understood, unexpected possibilities can underline risk-based, probabilistic assessments. Such deep uncertainties can manifest in ways that cannot be characterised probabilistically or be assigned a likelihood of occurrence (*149*). These uncertainties are often epistemological, stemming from inadequate theoretical frameworks, vague boundaries defining food systems, or differing social values in measuring sustainability (i.e., known unknowns).

With probabilistic frameworks ill-equipped to handle deep uncertainty, some food system modelling studies have adopted scenario-based approaches. While powerful and practical, these approaches are often constrained by computational limits, restricting these studies to a small number of scenarios typically based on shared socioeconomic pathways. For instance, emissions-neutral food systems were modelled using five scenarios in MAgPIE (*71*) and four in IMAGE (*150*). Although scenarios are valuable tools, especially when developed through participatory processes that incorporate the shared visions and priorities of diverse stakeholders, they can limit the full range of variability in sustainability impacts observed across other studies (*151-153*). In essence, an overly narrow focus on predefined assumptions about future possibilities may restrict the scope for a broader and more robust exploration of transformation pathways. Another consequence of this is that while models are often promoted for their ability to support what-if scenarios analysis of key policy choices, there is a risk that this use could inadvertently sideline broader discussions about relevant scenarios, particularly in contexts where scenarios are designed in more top-down or less participatory ways (*154*). Encouraging a more open and inclusive dialogue around these models and their scenarios could help ensure that their insights are used without prematurely closing off debate.

There are also other approaches that can improve the robustness of modelling results to some forms of deep uncertainty. Among them to improve robustness is the systematic exploration of uncertainty space through large scenario ensembles (*155*). Although such ensembles may not be a representative of full system variability, they can still represent a more diverse assumptions about boundary conditions, indicators, and model structures and parameters, enabling a more comprehensive analysis of future possibilities (*156*). One way to operationalise ensemble approaches is through multi-model assessments, such as in AgMIP (*157*), which integrates projections from various models to characterise uncertainty while addressing inconsistencies in data and assumptions (*7, 158, 159*). While effective, implementing scenario ensembles necessitates addressing two key challenges: the computational burden of running ensemble simulations across multiple models and the complexity of synthesising, interpreting, and communicating scenario results, as we elaborate in the following.

Running scenario ensembles can be computationally expensive, with a single model run ranging from minutes to days, depending on the model type, software implementation, and available computational resources. To address this computational burden, various approaches rooted in surrogate modelling have been developed (*160*). Surrogate models provide simplified, computationally efficient alternatives to complex, resource-intensive models. These models, often based on statistical methods or machine learning, emulate the behaviour of more complex systems, enabling a more efficient exploration of uncertainty across various model inputs (see Model Snapshot 3). Surrogate modelling has been widely applied in uncertainty assessments across domains such as food demand, food system change, land-use sustainability, and soil carbon sequestration (*49, 156, 161-163*).

Interpreting and synthesising the extensive modelling results from scenario ensembles is challenging, as the generated scenarios may not fully or evenly capture the uncertainty space, unlike traditional probabilistic approaches to uncertainty assessment. Moreover, reconciling differences between independently developed models, while essential for exploring model structural and dataset uncertainties, adds further complexity to the integration process (*36, 164*). This complexity is amplified when communicating results to model users and decision-makers. Advanced visualisation techniques and data-mining methods like clustering can help simplify interpretation, making results more practical for users (*165*).

Beyond these forms of uncertainties, these are unpredictable and unforeseen challenges or opportunities that could arise during food system transformation and represent events or developments that are entirely outside current expectations or planning frameworks (e.g., impact of pandemic or geopolitical conflict on supply chain) and are unmeasurable through modelling (e.g., the politics of risk and uncertainty around genetically modified crops) (*166*). Navigating such uncertainties demands more adaptive and pluralistic approaches that involve continuously assessing and monitoring changes as they evolve and prioritising flexibility, experimentation, and learning over relying on the prevailing assumption that can engineer pathways to a desired future. While there are analytical frameworks, such as robust decision-making and adaptive policy pathways, that can be used to derive more practical decision insights under such uncertainties (*25, 167*), effectively addressing these uncertainties ultimately demands a fundamental rethinking of policies, institutions, and practices. This shift involves prioritising incremental learning and adaptation in response to evolving, uncertain environments (i.e., the concept of 'muddling through') (*168, 169*).

Model Snapshot 3. A global food system transformation within environmental limits

By pooling together inputs and outputs from 63 diverse food system modelling studies and their underlying scenarios, Hadjikakou *et al.* (*156*) used surrogate modelling to carry out a quantitative synthesis of the global food system literature. This was aimed at assessing the individual and combined effect size of key interventions in terms of mitigating the risk of exceeding global environmental limits (*170*), considering a comprehensive range of key methodological assumptions made in other models.

Hadjikakou *et al.* (*156*) first assembled a comprehensive database of environmental impact estimates against 8 key environmental indicators covering land-system change, freshwater use, climate change, and biogeochemical flows, impacted by the global food system based on a systematic review of 63 global food system scenario modelling studies. Second, they identified 10 major demand- and supply- side interventions and extracted relevant data to create a set of harmonised quantitative input variables (e.g., crop yields, feed efficiency, dietary composition) to parameterise these interventions. A set of statistical models were then developed by using the compiled data to fit a linear mixed-effects meta-regression model for each environmental indicator using the harmonised intervention variables as predictors and environmental impacts as dependent variables. Using the statistical models, they simulated all plausible intervention combinations considering four representative ambition levels of implementation to yield mean estimates and prediction intervals for each environmental indicator in 2050. Finally, Hadjikakou *et al.* (*156*) used probabilistic risk assessment (*171*) to calculate the risk of exceeding environmental limits associated with each intervention level combination using the statistical models (Figure 3).

While the resulting statistical models assume a linear response to the various scenarios drivers and cannot explicitly incorporate the complex dynamics of process-based models, their significant advantage is that they can run at a fraction of the time compared to more computationally intensive models typically used in food system studies. This allows many thousands or millions of scenarios encompassing a much more complete range of possible futures.

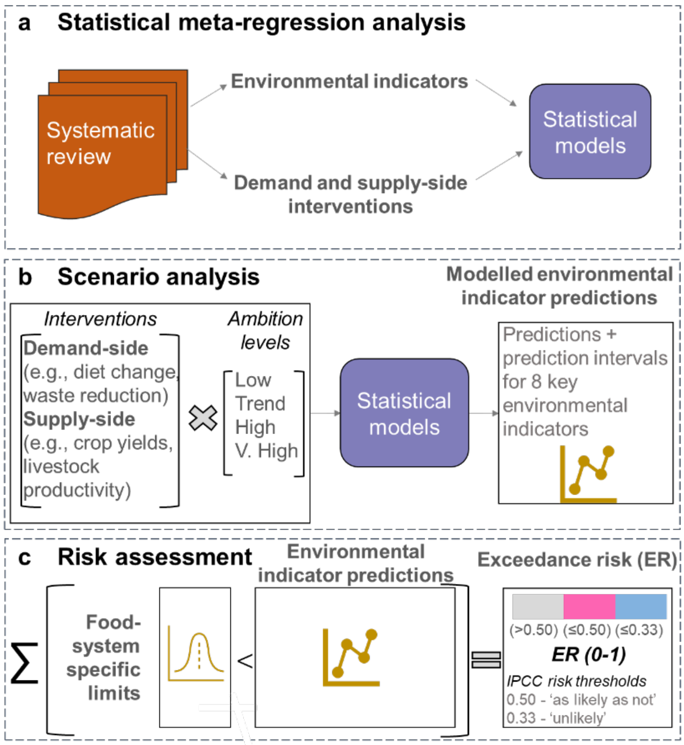


Figure 3. Overview the meta-analysis process.

4.4. Evolving Needs and Scenarios

The increase in the number of new scenarios, novel technology and policy options, and emerging environmental and societal indicators to be measured and explored quantitatively creates a significant challenge for modelling frameworks to remain responsive to these evolving needs of food system transformation. Understanding and leveraging new socioeconomic assumptions, such as circular economies, degrowth, and green growth models, has become increasingly critical (*71, 114, 172*). Future technologies and policies spanning production (e.g., agroecology, precision agriculture) to consumption (e.g., dietary improvements, waste reduction) carry both intended and unintended consequences for reshaping food systems that require in-depth exploration (*73, 173*). Emerging indicators, such as the interplay between human and planetary well-being or multidimensional inequality, are also becoming central to transformation efforts, yet they are rarely explicitly projected by current models (*174*). Achieving these insights sometimes cannot afford delays from years-long development of new models or reconfiguration of existing ones.

There is also an increasing number of new stakeholders, bringing fresh perspectives and seeking innovative applications for model-based insights. Beyond the traditional users, financial institutions, corporations, and industries are now leveraging models to assess the risks and benefits of transitioning to more sustainable practices, as well as to identify cost-optimised pathways for resilient investments (*175*). Similarly, NGOs and civil society organisations are exploring new use-cases, utilising models as tools to facilitate community engagement and develop governance mechanisms that support transformative change (*176*). However, the rapid pace of change in food systems, coupled with the shorter timelines for investment, policymaking, and action, often contrasts with the longer timeframes required for model development and refinement. This mismatch can create significant barriers to the usability of models, limiting their ability for direct engagement with end users to respond to their evolving needs.

To meet these evolving needs, food system models need to be capable of generating fresh insights for a diverse range of use-cases within shorter assessment cycles. This requires a deep understanding of the changing problem context and close connection to stakeholders. Modelling that is disconnected from decision-making processes can limit the translation of model outputs into actionable policy insights. Embedding modelling in participatory processes remains a significant challenge for modelling frameworks but one that is necessary to foster collaboration, transparency and trust, and ensure models remain policy and decision-making relevant. In prioritising participatory approaches, bringing collaborative design thinking to the modelling process seems to be essential to ensure that models remain relevant, usable, and adaptable to changing demands over time, ultimately leading to more effective solutions that better align with the diverse interests of all parties involved (*177*).

Addressing stakeholder needs within shorter assessment cycles often favours models of intermediate complexity, that trade off precision against ease of calibration to new applications via reduced data requirements and modular, parsimonious design (*178, 179*). Intermediate complexity enables faster building while allowing for effective user feedback and iteration (see Model Snapshot 4). Such simpler models are not intended to replace larger models, and there should be part of the portfolio of diverse models used to serve different purposes in informing food system transformation. Similarly important is the focus on user interfaces and integrating interactive visual analytics tools. These tools can effectively communicate, visualise, and translate model results for a wider range of end-users (*165*). Such tools have been designed and exist already to enable the exploration of projected global food security (*49, 180*), sustainability trade-offs arising from agricultural land uses (*46, 181*), and impacts of labour conditions on food production (*46, 181*). Enhancing usability through these tools can increase model relevance, address current accessibility gaps, and support applications in decision-making across government, industry, business, and civil society.

Model Snapshot 4. Globally consistent national pathways towards sustainable food and land

The Food, Agriculture, Biodiversity, Land and Energy (FABLE) Calculator is a MS Excel-based model that represents the dynamics of national food and land use systems in simple terms and in relation to food production, food demand, biodiversity (via land use occupation), emissions, water use and trade (*182*). The calculator is pre-set to represent a specific world country using global datasets from sources (e.g., FAO, IIASA), and country teams from the FABLE Consortium refine and calibrate their calculator using the best available in-country data and knowledge. The FABLE Calculator represents the effect of changes as exogenous assumptions in relation to agricultural practices, consumption patterns (e.g., diets), and policies on a range of outcome indicators related to food, agriculture, biodiversity, land and energy (FABLE) outcomes in 5-yearly timesteps in a transparent manner.

The FABLE Calculator is a tool that allows for rapid prototyping and iteration with users, provided that the right data to parametrise scenarios can be elicited. For example, in the 2019 and 2020, the Australian country calculator introduced livestock density growth scenarios, which subsequently helped better understand the potential impacts of increased livestock production on resource use and sustainability in the agricultural sector (*33*). The system of national FABLE Calculators and other process-based models linked using a tool called FABLE Linker which aggregates the national results into global results offered a novel way to address global policy questions while taking into consideration the socio-economic and political circumstances of each country (*132*).

The FABLE Calculator also offered full transparency of data, formulas and results as it is a collection of Excel spreadsheets, which can be opened to see the input and output values, and make changes to them as necessary. However, the number of tables, columns, and formulas can quickly become overwhelming and therefore an obstacle to new users. In some country versions of the Fable Calculator (e.g., Australia), there is a functionality that allows users to control the entire model from a single central table where they can define which variables act as stochastic inputs (minimum and maximum value for each variable) and which ones to track as outputs. This allows the model to run 1000 iterations in five minutes. The data generated by these iterations can then be visualised in a series of density plots and a correlation matrix to display the strength of the relationship between inputs and outputs, and summary figures and tables to quantify the likelihood of achieving concurrent FABLE targets under different scenarios. This information can be compared with existing countries' commitments to analyse whether they are likely to be compatible with long term sustainability of the land use sector.

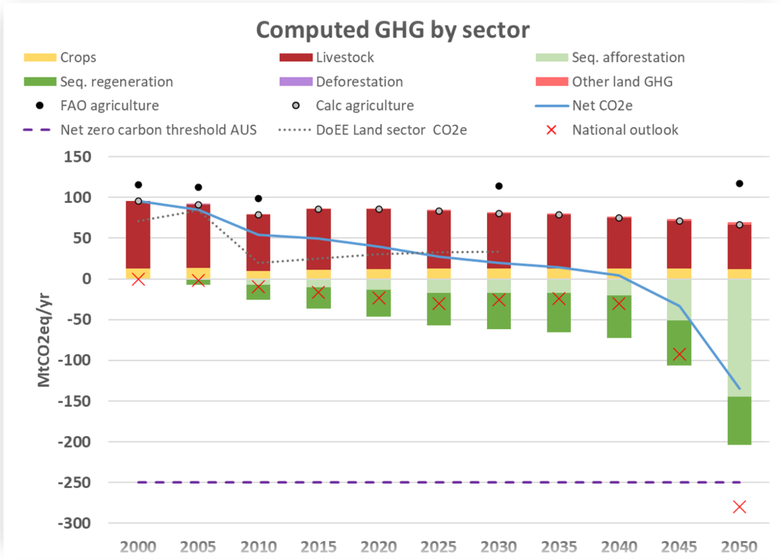


Figure 4. An example of the Australian FABLE Calculator's outputs, i.e., GHG emissions by sector and year for the sustainability pathway scenario

5. MANAGING TENSIONS AND TRADEOFFS

Throughout the challenges and opportunities discussed, balancing complexity and simplicity in food system modelling may imply inherent tensions and trade-offs. While greater complexity is often necessary to capture uncertainties, local-system characteristics, and socio-political drivers, overly complex models risk becoming opaque, computationally demanding, and inaccessible to stakeholders. Conversely, simpler models enable rapid prototyping and scenario exploration but may oversimplify critical dynamics, potentially compromising utility.

Addressing these tensions requires rethinking model design, purpose, and application via participatory processes. It also requires a deep understanding of how computational models can support human decision-making. A key issue is whether models are seen as providing detailed scenario solutions to decision makers who consequently require a deep understanding of model strengths and weaknesses to interpret results appropriately and choose a course of action, or whether model results are seen as one of many diverse influences on the heuristics that decision makers use to manage deep uncertainty. A general principle is the more sophisticated models do not necessarily predict outcomes better in terms of predictability and support for decision-making (*183*). Moreover, no single model can encompass every dimension and scale of a complex, uncertain process like food system transformation. Instead, different models are suited to different tasks, and their limitations should be explicitly acknowledged, addressed, and communicated to their users. Several studies of other systems like energy and climate have acknowledged the limitations of models that formalise multi-sector dynamics and called for more holistic analyses through a more diverse range of models (*37, 155, 184, 185*). As with other complex systems, transforming food systems also demands a spectrum of models, each tailored to specific objectives. These models should leverage their unique strengths and complement one another to construct a comprehensive understanding of the change process.

Within this context, a promising path forward would be adopting modular and interoperable modelling frameworks that promotes transparency, interchangeability, and adaptability. Inspired by practices in Earth system modelling (*186*) and systems engineering architecture (*187*), this approach emphasises establishing and agreeing on standards and protocols for data, modelling, and interoperability and allows for "plug-and-play" functionality, where components can be adapted or replaced as needed, allowing models to be flexible and scalable.

The demand for flexibility and interchangeability also highlights the need to strengthen the coupling of models to better capture the complexity and uncertainty inherent in the transformation of food systems through the strengths of different modelling frameworks (see Model Snapshot 5). For example, this approach could support the development of a multi-resolution model for complex systems. Initially, a model of high-level abstraction can facilitate ensemble methods for exploring uncertainties, offering broad insights across scenarios. Subsequently, a full-resolution model can delve deeper into specific behaviours of interest, providing detailed analysis where needed. This layered and adaptable approach ensures that models are robust and practical, and effectively address the challenges posed by complexity and uncertainty.

Model Snapshot 5. Model coupling for a more comprehensive framing of food system transformation

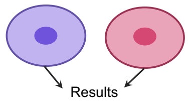
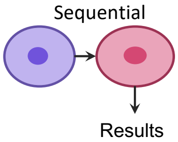
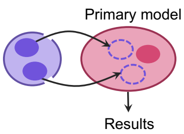
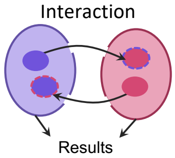
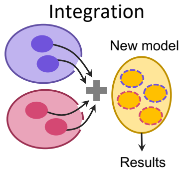
Model coupling is already a well-established practice in partial and general equilibrium modelling, as well as in integrated assessment modelling in food and agriculture. However, there is still much to learn from the decision support and operations research communities' practices (*188*), particularly in exploring various ways to combine multiple models. These could offer insights into how coupling can be structured and the strategic choices involved in integrating diverse models to leverage their unique strengths.

The simplest type of coupling is *parallel*, where models operate independently within harmonised boundaries to provide complementary insights or enable comparability, as seen in multi-model intercomparison and ensemble modelling projects (*36*). However, the future states of food systems generated via a parallel coupling are not statistically representative and may skew results towards dominant models. *Sequential* coupling involves one model informing another in a one-way relationship, such as demographic models projecting food demand for spatial land-use models (*189*). While this ensures detailed process representation and transparency, it often lacks feedback between system components.

Another type of coupling is *enhancement*, which integrates elements of one model into another to enrich its scope, as demonstrated by the FeliX model's analysis of diet shift incorporating C-ROADS for carbon cycle formalisation (*107*). This allows for systematic uncertainty assessment and generation of statistically representative scenarios but adds computational complexity. *Interaction*, another type of coupling, involves models remain independent operating within their own distinct frameworks exchange data iteratively to address each other's needs. For instance, the soft coupling of REMIND and MAgPIE iteratively aligns assumptions about bioenergy, emissions, and costs, enabling consistent scenario generation (*70*). This type of coupling provides system feedback but requires intensive coordination and synchronisation.

Integration represents the most advanced form of coupling, merging multiple models into a unified framework to create a coherent system. This approach, as seen in surrogate models using regression analysis (*156*) or machine learning methods (*190*), enables structured scenario ensembles with probabilistic insights. However, integration increases complexity, requiring careful assessment of its impact on model development and testing. The choice of a collaboration form between models for conducting an integrated assessment of food system transformation ultimately depends on the context of the assessment and the needs of stakeholders (see Table 2).

Table 2. Overview of different types of model coupling (adapted from Morgan *et al.* (*188*) and Moallemi *et al.* (*191*))

Type of coupling	Direction, form, frequency of exchange	Implementation	Advantage	Disadvantage
Parallel 	No interaction	Built in one or two modelling frameworks	• Complementary insights from multiple views	• Little flexibility in exploring uncertainty
Sequential 	One-way; model insights and hard data; single frequency	Built in one or two modelling frameworks	• Improved traceability and controlled complexity	• Lack of endogenous feedback • Potential inconsistencies
Enhancement 	One- or two-way; hard data; high frequency	Built in one unified modelling framework	• Endogenous feedback (hard coupling) • High internal consistency • Structured scenarios for uncertainty assessment	• Need for new testing and validation • Increased complexity and intransparency
Interaction 	One- or two-way; model insights and hard data; limited frequency	Built in one or two modelling frameworks	• Improved traceability and controlled complexity • Assessment of feedback (soft coupling)	• Little flexibility in exploring uncertainty • Potential inconsistencies
Integration 	Two-way; hard data; high frequency	Built in one unified modelling framework	• Endogenous feedback (hard coupling) • High internal consistency • Structured scenarios for uncertainty assessment	• Need for new testing and validation • Increased complexity and intransparency

While recognising potential tensions and trade-offs, we argue that these tensions can sometimes also be a symptom of more fundamental problem; a problem that lies in a conventional aspiration to create an "ultimate" all-encompassing model and therefore find tensions in consolidating all features discussed in Section 4 into a single package. Such an aspiration is often driven by the view that adding more details inherently increases accuracy or effectiveness (*192, 193*). We acknowledge that given the highly complex and deeply uncertain nature of food system transformations and their interactions, it is unlikely that we will ever "fully" understand them or be able to "control" them, so this shouldn't be the end goal. The tensions between different features for modelling food system transformations can also stem from the understanding of what complexity means and how it should be addressed in models. Complexity does not always equate to large, highly detailed, and data-intensive models. Instead, it arises from non-linear interactions, feedback loops, and emergent phenomena, which can all exist in models with relatively simple structures (*194, 195*). For example, the logistic map, a single-variable deterministic equation, can produce complex behaviour through non-linear dynamics, demonstrating that complexity is not solely dependent on the number of components (*196*).

While these issues can have varying degrees of implications across models, there are existing modelling efforts that have experienced at least some of these issues (*197*). In balancing between complexity and simplicity, a path forward is question-driven (*198*) and participatory modelling where stakeholders, such as users, are more genuinely involved during model design and development to ensure that the level of complexity aligns with the specific questions, uncertainties, and decision priorities tailored to the context. The push for more detailed models can be also guided by techniques such as uncertainty and sensitivity analysis (*199*), which help modellers understand the relationship between model complexity and uncertainty and identify the most influential aspects of the model that needs further specification (*200*). This enables modellers to recognise when adding further detail no longer improves the model and allows for a better calibration of model complexity to suit the specific context and application (*193*).

6. CONCLUSIONS

Relying on a narrow set of models to guide food system transformation risks limiting the range of pathways and missing the full potential of what food systems can achieve. The transformation of food systems towards a more sustainable future is inherently complex and uncertain, and this poses challenges to the relevance and utility of models relied on in the past. A tendency to overlook complexity and uncertainty can hinder identification of actionable insights for real-world change. An inability to model socio-political drivers, power dynamics, and human feedback loops risks favouring technically idealistic solutions that may ignore pragmatic contextual realities. And there is no need to perpetuate these limitations. Alternative approaches are evolving that can address these challenges by enhancing the endogenous representation of socio-political drivers, improving model robustness in the face of uncertainty, ensuring that models capture multi-scale, context-specific dynamics, and that enable adaptation of participatory process to meet emerging stakeholder needs. These represent dimensions against which future models and their usefulness could be interrogated and checked.

No single model can fully capture the complexity of food system transformation; at best, all models are only approximations of the reality and dynamics at play. But this is consistent with the boundaries on knowledge that constrain human decision-making, which mean that model complexity works against model utility in supporting decision-making. Addressing the complexity and uncertainty of transformation requires a diverse array of models using different analytical approaches that enable more comprehensive analysis and interpretation of the impacts of various policy options. These need to be embedded in responsive participatory processes that facilitate dynamic recombination of model capability to meet evolving needs.

The analysis and discussion of this paper represents only the tip of an iceberg. We aimed to provide an overview of commonly used food system models by classifying them based on their ability to simulate different dimensions of the food system. However, the level of detail and complexity can vary significantly across models for each dimension, even with the same classification. Future research could improve the representation of this complexity by incorporating insights from experts and model developers. We see a clear opportunity for a more thorough review of the successes and limitations of food system models for transformation, which would deepen our understanding, broaden analytical perspectives, and help identify more effective pathways for future food systems.

Acknowledgment

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Appendix A

Partial Equilibrium (PE) Models

These models focus on specific sectors of the economy, such as agriculture, and assume that changes in this sector do not significantly affect the rest of the economy. Some of these models include a spatially explicit, gridded representation of agriculture. Compared to other types of models, some partial equilibrium models with a gridded representation of land use allow more detailed representation of land-use trade-offs (*91*) and of environmental outcomes (*201, 202*). However, because partial equilibrium models focus on a specific part of the economy, they lack broader economic interactions with other sectors. These models can significantly differ in their methodological approaches, for instance, whether they depict bi-lateral or just net-trade. Demand is expressed in these models based on so-called 'primary product equivalent' (i.e., in units of the primary products they are derived from. Quantities are measured in physical units). Market clearing is achieved by adjusting prices. Partial equilibrium models are most commonly used to analyse changes in economic outcomes of the food system (often agricultural) production, consumption, trade, and prices. They were developed from food balance sheets which have been in continuous use since at least 3500 years BC (*203*).

Some key features of the selected six PE model are given in the list below:

1. *IMPACT*: The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) is a spatially explicit recursive-dynamic net-trade model developed by the International Food Policy Research Institute (IFPRI). The model focuses on global food supply and demand, trade, and food security (*53, 204-206*)
2. *GLOBIOM*: The Global Biosphere Management Model (GLOBIOM) is a spatially explicit recursive-dynamic model that combines agricultural, forestry, and bioenergy sectors to analyse land-use dynamics, food production, and environmental impacts, developed by the International Institute for Applied System Analysis (IIASA) (*52, 207, 208*). It is based on explicit optimisation including the minimisation of international transport cost and production costs to satisfy demand.
3. *MAgPIE*: The Model of Agricultural Production and its Impact on the Environment (MAgPIE) is a spatially explicit recursive-dynamic model that combines economic and biophysical approaches to simulate spatially explicit global scenarios of land use until 2100 and the respective interactions with the environment, developed by the Potsdam Institute for Climate Impact Research (PIK) (*54*).
4. *CAPRI*: The Common Agricultural Policy Regional Impact model (CAPRI) is a detailed comparative static partial equilibrium model for the European agricultural sector, used for policy impact assessment on agriculture, environment, and rural areas, developed by the European Commission (*123*). Europe is depicted by technology rich programming models at subnational level which are iteratively coupled with a global PE, which depicts bi-lateral trade based on the Armington assumption and draws on theory-consistent demand and supply function.
5. *AgLINK-COSIMO*: AGricultural LINKage - COmmodity SImulation Model (AGLINK-COSIMO) is a net-trade recursive-dynamic, partial equilibrium, supply–demand model of world agricultural markets developed jointly by the Organization for Economic Cooperation and Development (OECD) and the Food and Agriculture Organization of the United Nations (FAO) Secretariats (*50*). The model is used to make projections 10 years into the future.
6. *SIMPLE-G*: The Simplified International Model of agricultural Prices, Land use, and the Environment-Gridded (SIMPLE_G) is a comparative static spatially-explicit version of the SIMPLE partial equilibrium agricultural trade model that has been validated for the study of long-run sustainability and food security (*55, 209*).

Global multi-regional Computable General Equilibrium (CGE) Models

These models consider the interactions between all sectors of the economy and can capture the broader economic impacts of changes in the agrifood system. General equilibrium models tend to be more uniformly structured than partial equilibrium models as they draw mostly on a set of standard assumptions: competitive markets for products and factors, utility maximising final demanders and cost-minimising representative firms, one in each sector. Many of the economic decisions are depicted by using Constant-Elasticity-of-Substitution (CES, production function, trade composition, part of final demand) and Constant-Elasticity-of-Transformation functions (CET, allocation of resources to sectors). Equations are usually templated such that models can be used with differently detailed database (regions, sectors). The databases informing these models include all sectors of the economy, but often less detailed with regard to agriculture and land use sector than partial equilibrium models. Some models, such as AIM, GTAP and GTEM, were initially developed without a specific focus on the agrifood sector but later incorporated applications related to the food system. In contrast, models like MAGNET and MIRAGRODEP have had an intrinsic focus on agricultural policy analysis since their inception. General equilibrium models are used to analyse interactions between sectors of the economy such as agriculture and food manufacturing.

7. *AIM/*CGE or AIM/HUB: The Asia-Pacific Integrated Model (AIM) general equilibrium model includes a detailed agricultural module to assess land use and food production in the context of climate change, developed by the National Institute for Environmental Studies (NIES) (*57, 210*).

8. CGEBox: CGEBox is a modular platform for CGE modelling departing from the GTAP Standard model (*58*). For food system analysis, it usually dis-aggregates the GTAP Database to rich agri-food detail (including rainfed and irrigated crops; open catch versus aquaculture), employs the GTAP-AEZ land-use component, uses detailed nesting in final demand and the production functions to depict substitution between closely related products, adds nutrient accounts and an empirical estimated MAIDADS demand system with food detail to depict income dynamics and uses either multiple households or a post-model micro-simulation to assess distributional aspects. It can be used in comparative or recursive-mode, for the latter, the G-RDEM component depicts important aspect of structural change dynamics (income dependent cost and expenditure shares, endogenous savings, sector differentiated productivity growth).

9. DART-BIO: DART-BIO is a variant of the Dynamic Applied Regional Trade (DART) model, a multi-sectoral, multi-regional recursive dynamic CGE model of the world economy, that includes land use (*59*). It was developed at the Kiel Institute for the World Economy.

10. *GTAP*: The Global Trade Analysis Project (GTAP) model is a global general equilibrium model with several variations, e.g., GTAP-W (*211*), GTAP-AEZ (*212*), GTAP-BIO (*213*), G-RDEM (*214*) and CGEBox (*58*), as well as DART-BIO and MAGNET covered separately in this section. The model is used for analysing international trade policies, including agricultural and environmental policies, developed by Purdue University (*211, 215*).

11. *GTEM:* The Global Trade and Environment Model (GTEM) is a dynamic, multiregional and multisectoral general equilibrium model of the global economy, developed originally by the Australian Bureau of Agricultural and Resources Economics (ABARE) (*61, 216*) with recently work led by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

12. *MAGNET:* The Modular Applied GeNeral Equilibrium Tool (MAGNET) is a recursive dynamic global general equilibrium model, a variant of the GTAP model, that includes a detailed agricultural sector module for analysing global food and agricultural policies, developed by Wageningen University (*62, 68*).

13. *MIRAGRODEP:* Modelling International Relations under Applied General Equilibrium model enhanced for the AGRODEP modeling consortium (MIRAGRODEP) is a recursive-dynamic, multi-

region, multi-sector computable general equilibrium model, developed by IFPRI for trade and agricultural policy analysis. It is developed for African Growth Development Policy (AGRODEP) and draws upon the Modelling International Relationships in Applied General Equilibrium (MIRAGE) model developed by Centre d'Etudes Prospectives et d'Informations Internationales (CEPII) (*63, 217*).

Integrated Assessment Models (standalone)

These models integrate economic, environmental, and social components to provide a holistic view of global changes and policies. These models tend to have representation of more than one sector, for instance agriculture, land use, and energy, but also have a simplified representation of the whole economy compared to general equilibrium models (*39*). They have evolved especially to recognise interactions between the environment (especially climate) and the economy (*39*).

14. *IMAGE*: The Integrated Model to Assess the Global Environment (IMAGE) model is an integrated assessment modelling framework that can be used to explore the long-term pathways for future environmental and sustainable development problems as well as possible response strategies, developed by the Netherlands Environmental Assessment Agency (PBL) (*65, 94*).
15. *GCAM:* The Global Change Assessment Model (GCAM) integrates energy, economy, land use, and water to assess climate change mitigation and adaptation policies, including their impacts on agriculture, developed by the Pacific Northwest National Laboratory's Joint Global Change Research Institute (*64*).

Coupled models

16. *IMAGE 3.0*: The IMAGE 3.0 framework is a suite of models combining the standalone IMAGE model with the MAGNET CGE model (*65, 150*).
17. *MESSAGEix-GLOBIOM*: The MESSAGEix-GLOBIOM integrated assessment framework is a global energy–economic–agricultural–land-use model developed at IIASA that couples the energy model MESSAGEix, the land-use model GLOBIOM (*208*), the air pollution and greenhouse gas (GHG) model GAINS, the aggregated macro-economic model MACRO, and the simple climate model MAGICC (*69, 218-220*).
18. *REMIND-MAgPIE*: The IAM REMIND-MAgPIE is developed by PIK and combines the energy-economy model REMIND (regional model of investments and development) with the food and land-use model MAgPIE (model of agricultural production and its impact on the environment) (*70, 221*).
19. *LandSyMM:* The Land System Modular Model (LandSyMM) integrates the Parsimonious Land Use Model (PLUMv2) is global land-use and food-system model, Lund-Potsdam-Jena general ecosystem simulator (LGJ_GUESS) and the modified, implicit, directly additive demand system (MAIDADS) demand model (*222, 223*).
20. Globe-IMPACT: The Globe-IMPACT framework couples the IMPACT partial equilibrium model of agriculture with the Globe model, a global CGE model based on a Social Accounting Matrix (SAM) and calibrated using data derived from the Global Trade Analysis Project's (GTAP) database (*66, 224-226*).

Appendix B

Table B1. Food system modelling papers reviewed to evaluate the selected models in Table 1 (main text).

Author	Year	Journal	Title
Alexander, P., Arneth, A., Henry, R., Maire, J., Rabin, S., Rounsevell, M.D.A.	2023	Nature Food	High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment
Alexander, P., Rabin, S., Anthoni, P., Henry, R., Pugh, T.A.M., Rounsevell, M.D.A., Arneth, A.	2018	Global Change Biology	Adaptation of global land use and management intensity to changes in climate and atmospheric carbon dioxide
Araujo Enciso, S.R., Fellmann, T., Pérez Dominguez, I., Santini, F.	2016	Food Policy	Abolishing biofuel policies: Possible impacts on agricultural price levels, price variability and global food security
Awais, M., Vinca, A., Byers, E., Frank, S., Fricko, O., Boere, E., Burek, P., Poblete Cazenave, M., Kishimoto, P.N., Mastrucci, A., Satoh, Y., Palazzo, A., McPherson, M., Riahi, K., Krey, V.	2024	Geosci. Model Dev.	MESSAGEix-GLOBIOM nexus module: integrating water sector and climate impacts
Bartelings, H., Philippidis, G.	2024	Sustainable Production and Consumption	A novel macroeconomic modelling assessment of food loss and waste in the EU: An application to the sustainable development goal of halving household food waste
Beckman, J., Estrades, C., Aguiar, A.	2019	Food Security	Export taxes, food prices and poverty: a global CGE evaluation
Beusen, A.H.W., Doelman, J.C., Van Beek, L.P.H., Van Puijenbroek, P., Mogollon, J.M., Van Grinsven, H.J.M., Stehfest, E., Van Vuuren, D.P., Bouwman, A.F.	2022	Global Environmental Change-Human and Policy Dimensions	Exploring river nitrogen and phosphorus loading and export to global coastal waters in the Shared Socio-economic pathways
Bjørndal, T., Dey, M., Tusvik, A.	2024	Aquaculture	Economic analysis of the contributions of aquaculture to future food security
Bodirsky, B.L., Dietrich, J.P., Martinelli, E., Stenstad, A., Pradhan, P., Gabrysch, S., Mishra, A., Weindl, I., Le Mouël, C., Rolinski, S., Baumstark, L., Wang, X., Waid, J.L., Lotze-Campen, H., Popp, A.	2020	Scientific Reports	The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection
Bodirsky, B.L., Popp, A., Weindl, I., Dietrich, J.P., Rolinski, S., Scheiffele, L., Schmitz, C., Lotze-Campen, H.	2012	Biogeosciences Discussions	Current state and future scenarios of the global agricultural nitrogen cycle
Bouët, A., Laborde, D.	2018	The World Economy	US trade wars in the twenty-first century with emerging countries: Make America and its partners lose again
Bouwman, A.F., Beusen, A.H.W., Griffioen, J., Van Groenigen, J.W., Hefting, M.M., Oenema, O., Van Puijenbroek, P.J.T.M., Seitzinger, S., Slomp, C.P., Stehfest, E.	2013	Philosophical Transactions of the Royal Society B: Biological Sciences	Global trends and uncertainties in terrestrial denitrification and N2O emissions
Bouwman, L., Goldewijk, K.K., Van Der Hoek, K.W., Beusen, A.H.W., Van Vuuren, D.P., Willems, J., Rufino, M.C., Stehfest, E.	2011	Proceedings of the National Academy of Sciences	Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period
Britz, W.	2022	Journal of Global Economic Analysis	Disaggregating Agro-Food Sectors in the GTAP Data Base

Author	Year	Journal	Title
Britz, W., Roson, R.	2019	Journal of Global Economic Analysis	G-RDEM: A GTAP-Based Recursive Dynamic CGE Model for Long-Term Baseline Generation and Analysis
Britz, W., Verburg, P.H., Leip, A.	2011	Scaling methods in integrated assessment of agricultural systems	Modelling of land cover and agricultural change in Europe: Combining the CLUE and CAPRI-Spat approaches
Britz, W., Witzke, P.	2014	NA	CAPRI model documentation 2014
Calvin, K., Fisher-Vanden, K.	2017	Environmental Research Letters	Quantifying the indirect impacts of climate on agriculture: an inter-method comparison
Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R.Y., Di Vittorio, A., Dorheim, K., Edmonds, J., Hartin, C., Hejazi, M., Horowitz, R., Iyer, G., Kyle, P., Kim, S., Link, R., McJeon, H., Smith, S.J., Snyder, A., Waldhoff, S., Wise, M.	2019	Geosci. Model Dev.	GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems
Calvin, K., Wise, M., Kyle, P., Patel, P., Clarke, L., Edmonds, J.	2014	Climatic Change	Trade-offs of different land and bioenergy policies on the path to achieving climate targets
Calzadilla, A., Rehdanz, K., Tol, R.S.J.	2010	Journal of Hydrology	The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis
Chang, J., Havlík, P., Leclère, D., Vries, W., Valin, H., Deppermann, A., Hasegawa, T., Obersteiner, M.	2021	Nature Food	Reconciling regional nitrogen boundaries with global food security
Chatzopoulos, T., Pérez Domínguez, I., Toreti, A., Adenäuer, M., Zampieri, M.	2021	Environmental Research Letters	Potential impacts of concurrent and recurrent climate extremes on the global food system by 2030
Chatzopoulos, T., Pérez Domínguez, I., Zampieri, M., Toreti, A.	2020	Weather and Climate Extremes	Climate extremes and agricultural commodity markets: A global economic analysis of regionally simulated events
Chen, M., Vernon, C.R., Graham, N.T., Hejazi, M., Huang, M., Cheng, Y., Calvin, K.	2020	Scientific Data	Global land use for 2015–2100 at 0.05° resolution under diverse socioeconomic and climate scenarios
Daioglou, V., Stehfest, E., Wicke, B., Faaij, A., Vuuren, D.P.	2016	GCB Bioenergy	Projections of the availability and cost of residues from agriculture and forestry
Debnath, D., Giner, C.	2019	Biofuels, Bioenergy and Food Security	Chapter 4 - Interaction between biofuels and agricultural markets, in: Debnath, D., Babu, S.C. (Eds.)
Delzeit, R., Heimann, T., Schünemann, F., Söder, M.	2021	Kiel Working Paper	DART-BIO: A technical description
Delzeit, R., Winkler, M., Söder, M.	2018	Sustainability	Land Use Change under Biofuel Policies and a Tax on Meat and Dairy Products: Considering Complexity in Agricultural Production Chains Matters
Dietrich, J.P., Bodirsky, B.L., Weindl, I., Humpenöder, F., et al.	2024	NA	MAgPIE - An Open Source land-use modeling framework - Version 4.9.0
Doelman, J.C., Beier, F.D., Stehfest, E., Bodirsky, B.L., Beusen, A.H.W., Humpenöder, F., Mishra, A., Popp, A., van Vuuren, D.P., de Vos, L., Weindl, I., van Zeist, W.-J., Kram, T.	2022	Environmental Research Letters	Quantifying synergies and trade-offs in the global water-land-food-climate nexus using a multi-model scenario approach

Author	Year	Journal	Title
Doelman, J.C., Stehfest, E., Tabeau, A., van Meijl, H., Lassaletta, L., Gernaat, D.E.H.J., Hermans, K., Harmsen, M., Daioglou, V., Biemans, H., van der Sluis, S., van Vuuren, D.P.	2018	Global Environmental Change	Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation
Doelman, J.C., Stehfest, E., Vuuren, D.P., Tabeau, A., Hof, A.F., Braakhekke, M.C., Gernaat, D.E.H.J., Berg, M., Zeist, W.-J., Daioglou, V., Meijl, H., Lucas, P.L.	2020	Global Change Biology	Afforestation for climate change mitigation: Potentials, risks and trade-offs
Elbersen, B., Fritsche, U., Petersen, J.-E., Lesschen, J.P., Böttcher, H., Overmars, K.	2013	Biofuels, Bioproducts and Biorefining	Assessing the effect of stricter sustainability criteria on EU biomass crop potential
Elleby, C., Domínguez, I.P., Adenauer, M., Genovese, G.	2020	Environmental and Resource Economics	Impacts of the COVID-19 Pandemic on the Global Agricultural Markets
Elleby, C., Jensen, H.G., Domínguez, I.P., Chatzopoulos, T., Charlebois, P.	2021	EuroChoices	Insects Reared on Food Waste: A Game Changer for Global Agricultural Feed Markets?
Escobar, N., Valin, H., Frank, S., Galperin, D., Wade, C. M., Ringwald, L., Tanner, D., Hinkel, N., Havlík, P., Baker, J. S., Lie, S., Ramig, C.	2025	Environmental Science & Technology	Understanding Uncertainty in Market-Mediated Responses to US Oilseed Biodiesel Demand: Sensitivity of ILUC Emission Estimates to GLOBIOM Parametric Uncertainty
Escobar, N., Haddad, S., Börner, J., Britz, W	2018	Environmental Research Letters	Land use mediated GHG emissions and spillovers from increased consumption of bioplastics
Fellmann, T., Domínguez, I.P., Witzke, P., Weiss, F., Hristov, J., Barreiro-Hurle, J., Leip, A., Himics, M.	2021	Journal of Cleaner Production	Greenhouse gas mitigation technologies in agriculture: Regional circumstances and interactions determine cost-effectiveness
Fellmann, T., Hélaine, S., Nekhay, O.	2014	Food Security	Harvest failures, temporary export restrictions and global food security: the example of limited grain exports from Russia, Ukraine and Kazakhstan
Ferrari, E., Roson, R. B., Britz, W., Dudu, H.	2019	Global Trade Analysis Project Conference papers	An extended myGTAP model to address subsistence production and sub-national households as a module in CGEBox
Frank, S., Beach, R., Havlík, P., Valin, H., Herrero, M., Mosnier, A., Hasegawa, T., Creason, J., Ragnauth, S., Obersteiner, M.	2018	Nature Communications	Structural change as a key component for agricultural non-CO2 mitigation efforts
Frank, S., Havlík, P., Soussana, J.-F., Levesque, A., Valin, H., Wollenberg, E., Kleinwechter, U., Fricko, O., Gusti, M., Herrero, M., Smith, P., Hasegawa, T., Kraxner, F., Obersteiner, M.	2017	Environmental Research Letters	Reducing greenhouse gas emissions in agriculture without compromising food security?
Frank, S., Havlík, P., Stehfest, E., van Meijl, H., Witzke, P., Pérez-Domínguez, I., van Dijk, M., Doelman, J.C., Fellmann, T., Koopman, J.F.L., Tabeau, A., Valin, H.	2019	Nature Climate Change	Agricultural non-CO2 emission reduction potential in the context of the 1.5 °C target
Frank, S., Lessa Derci Augustynczik, A., Havlík, P., Boere, E., Ermolieva, T., Fricko, O., Di Fulvio, F., Gusti, M., Krisztin, T., Lauri, P., Palazzo, A., Wögerer, M.	2024	Nature Food	Enhanced agricultural carbon sinks provide benefits for farmers and the climate

Author	Year	Journal	Title
Fujimori, S., Hasegawa, T., Ito, A., Takahashi, K., Masui, T.	2018	Scientific Data	Gridded emissions and land-use data for 2005–2100 under diverse socioeconomic and climate mitigation scenarios
Fujimori, S., Hasegawa, T., Krey, V., Riahi, K., Bertram, C., Bodirsky, B.L., Bosetti, V., Callen, J., Després, J., Doelman, J., Drouet, L., Emmerling, J., Frank, S., Fricko, O., Havlik, P., Humpenöder, F., Koopman, J.F.L., van Meijl, H., Ochi, Y., Popp, A., Schmitz, A., Takahashi, K., van Vuuren, D.	2019	Nature Sustainability	A multi-model assessment of food security implications of climate change mitigation
Fujimori, S., Hasegawa, T., Masui, T.	2017a	Post-2020 Climate Action: Global and Asian Perspectives	AIM/CGE V2.0: Basic Feature of the Model
Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K.	2014	Food Security	Land use representation in a global CGE model for long-term simulation: CET vs. logit functions
Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D.S., Dai, H., Hijioka, Y., Kainuma, M.	2017b	Global Environmental Change	SSP3: AIM implementation of Shared Socioeconomic Pathways
Fujimori, S., Kubota, I., Dai, H., Takahashi, K., Hasegawa, T., Liu, J.-Y., Hijioka, Y., Masui, T., Takimi, M.	2016	Environmental Research Letters	Will international emissions trading help achieve the objectives of the Paris Agreement?
Fujimori, S., Wu, W., Doelman, J., Frank, S., Hristov, J., Kyle, P., Sands, R., van Zeist, W.-J., Havlik, P., Domínguez, I.P., Sahoo, A., Stehfest, E., Tabeau, A., Valin, H., van Meijl, H., Hasegawa, T., Takahashi, K.	2022	Nature Food	Land-based climate change mitigation measures can affect agricultural markets and food security
Gatto, A., Kuiper, M., Middelaar, C., Meijl, H.	2024	Resources, Conservation and Recycling	Unveiling the economic and environmental impact of policies to promote animal feed for a circular food system
Gatto, A., Kuiper, M., van Meijl, H.	2023	Nature Food	Economic, social and environmental spillovers decrease the benefits of a global dietary shift
Gidden, M.J., Riahi, K., Smith, S.J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D.P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J.C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E., Takahashi, K.	2019	Geosci. Model Dev.	Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century
Godfray, H.C.J., Mason-D'Croz, D., Robinson, S.	2016	Philosophical Transactions of the Royal Society B: Biological Sciences	Food system consequences of a fungal disease epidemic in a major crop
Goebel, T., & Britz, W.	2023	The 26th Annual Conference on Global Economic Analysis (Bordeaux, France)	A Computable General Equilibrium Modelling Approach to Assess Biodiversity Effects in Highly Detailed Global Long-Run Analysis
Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B.L., Doelman, J.C., Fellmann, T., Kyle, P., Koopman, J.F.L., Lotze-Campen, H., Mason-D’Croz, D., Ochi, Y., Pérez	2018	Nature Climate Change	Risk of increased food insecurity under stringent global climate change mitigation policy

Author	Year	Journal	Title
Domínguez, I., Stehfest, E., Sulser, T.B., Tabeau, A., Takahashi, K., Takakura, J.y., van Meijl, H., van Zeist, W.-J., Wiebe, K., Witzke, P.			
Hasegawa, T., Fujimori, S., Ito, A., Takahashi, K., Masui, T.	2017	Science of the Total Environment	Global land-use allocation model linked to an integrated assessment model
Hasegawa, T., Fujimori, S., Shin, Y., Tanaka, A., Takahashi, K., Masui, T.	2015a	Environmental Science & Technology	Consequence of Climate Mitigation on the Risk of Hunger
Hasegawa, T., Fujimori, S., Takahashi, K., Masui, T.	2015b	Environmental Research Letters	Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways
Hasegawa, T., Sakurai, G., Fujimori, S., Takahashi, K., Hijioka, Y., Masui, T.	2021	Nature Food	Extreme climate events increase risk of global food insecurity and adaptation needs
Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M.C., Mosnier, A., Thornton, P.K., Böttcher, H., Conant, R.T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., Notenbaert, A.	2014	Proceedings of the National Academy of Sciences	Climate change mitigation through livestock system transitions
Heimann, T., Delzeit, R.	2024	Ecological Economics	Land for fish: Quantifying the connection between the aquaculture sector and agricultural markets
Henry, R.C., Arneth, A., Jung, M., Rabin, S.S., Rounsevell, M.D., Warren, F., Alexander, P.	2022	Nature Sustainability	Global and regional health and food security under strict conservation scenarios
Hertel, T.W., Baldos, U.L.C.	2016	Global Change and the Challenges of Sustainably Feeding a Growing Planet	Climate Change Impacts in Agriculture
Hertel, T.W., Golub, A.A., Jones, A.D., O'Hare, M., Plevin, R.J., Kammen, D.M.	2010	Bioscience	Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-mediated Responses
Ho, M., Britz, W., Delzeit, R., Leblanc, F., Roson, R., Schuenemann, F., Weitzel, M.	2020	Journal of Global Economic Analysis	Modelling Consumption and Constructing Long-Term Baselines in Final Demand
Humpenöder, F., Bodirsky, B.L., Weindl, I., Lotze-Campen, H., Linder, T., Popp, A.	2022	Nature	Projected environmental benefits of replacing beef with microbial protein
Humpenöder, F., Popp, A., Dietrich, J.P., Klein, D., Lotze-Campen, H., Bonsch, M., Bodirsky, B.L., Weindl, I., Stevanovic, M., Müller, C.	2014	Environmental Research Letters	Investigating afforestation and bioenergy CCS as climate change mitigation strategies
Islam, S., Cenacchi, N., Sulser, T.B., Gbegbelegbe, S., Hareau, G., Kleinwechter, U., Mason-D'Croz, D., Nedumaran, S., Robertson, R., Robinson, S., Wiebe, K.	2016	Global Food Security	Structural approaches to modeling the impact of climate change and adaptation technologies on crop yields and food security
Jansakoo, T., Sekizawa, S., Fujimori, S., Hasegawa, T., Oshiro, K.	2024	Sustainability Science	Benefits of air quality for human health resulting from climate change mitigation through dietary change and food loss prevention policy
Janssens, C., Havlík, P., Boere, E., Palazzo, A., Mosnier, A., Leclère, D., Balkovič, J., Maertens, M.	2022	Nature Food	A sustainable future for Africa through continental free trade and agricultural development

Author	Year	Journal	Title
Janssens, C., Havlík, P., Krisztin, T., Baker, J., Frank, S., Hasegawa, T., Leclère, D., Ohrel, S., Ragnauth, S., Schmid, E., Valin, H., Van Lipzig, N., Maertens, M.	2020	Nature Climate Change	Global hunger and climate change adaptation through international trade
Jansson, T., Säll, S.	2018	Climate Change Economics	Environmental Consumption Taxes on Animal Food Products to Mitigate Greenhouse Gas Emissions from the European Union
Jafari, Y., Himics, M., Britz, W., & Beckman, J.	2021	Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie	It is all in the details: A bilateral approach for modelling trade agreements at the tariff line
Jafari, Y., Britz, W., Dudu, H., Roson, R., Sartori, M.	2020	German Journal of Agricultural Economics	Can food waste reduction in Europe help to increase food availability and reduce pressure on natural resources globally?
Jeetze, P.J., Weindl, I., Johnson, J.A., Borrelli, P., Panagos, P., Molina Bacca, E.J., Karstens, K., Humpenöder, F., Dietrich, J.P., Minoli, S., Müller, C., Lotze-Campen, H., Popp, A.	2023	Nature Communications	Projected landscape-scale repercussions of global action for climate and biodiversity protection
JGCRI	2023	NA	GCAM Documentation (Version 7.0)
Kavallari, A., Fellmann, T., Gay, S.H.	2014	Food Security	Shocks in economic growth shocking effects for food security?
Klein, D., Luderer, G., Kriegler, E., Strefler, J., Bauer, N., Leimbach, M., Popp, A., Dietrich, J.P., Humpenöder, F., Lotze-Campen, H., Edenhofer, O.	2014	Climatic Change	The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE
Kompas, T., Che, T.N., Grafton, R.Q.	2024	Scientific Reports	Global impacts of heat and water stress on food production and severe food insecurity
Kozicka, M., Havlík, P., Valin, H., Wollenberg, E., Deppermann, A., Leclère, D., Lauri, P., Moses, R., Boere, E., Frank, S., Davis, C., Park, E., Gurwick, N.	2023	Nature Communications	Feeding climate and biodiversity goals with novel plant-based meat and milk alternatives
Kyle, P., Ollenburger, M., Zhang, X., Niazi, H., Durga, S., Ou, Y.	2023	Earth's Future	Assessing Multi-Dimensional Impacts of Achieving Sustainability Goals by Projecting the Sustainable Agriculture Matrix Into the Future
Laborde, D., Herforth, A., Headey, D., de Pee, S.	2021a	Nature Food	COVID-19 pandemic leads to greater depth of unaffordability of healthy and nutrient-adequate diets in low- and middle-income countries
Laborde, D., Mamun, A., Martin, W., Piñeiro, V., Vos, R.	2021b	Nature Communications	Agricultural subsidies and global greenhouse gas emissions
Laborde, D., Martin, W., Vos, R.	2021c	Agricultural Economics	Impacts of COVID-19 on global poverty, food security, and diets: Insights from global model scenario analysis
Laborde, D., Torero, M.	2023	Science and Innovations for Food Systems Transformation	Modeling Actions for Transforming Agrifood Systems

Author	Year	Journal	Title
Laborde, D., Valin, H.	2012	Climate Change Economics	Modeling Land-Use Changes in a Global Cge: Assessing the Eu Biofuel Mandates with the Mirage-Biof Model
Laborde Debucquet, D., Martin, W.	2018	Agricultural Economics	Implications of the global growth slowdown for rural poverty
Latka, C., Parodi, A., Hal, O., Heckelei, T., Leip, A., Witzke, H.-P., Zanten, H.H.E.	2022	Resources, Conservation and Recycling	Competing for food waste – Policies' market feedbacks imply sustainability tradeoffs
Le Page, Y., West, T.O., Link, R., Patel, P.	2016	Geoscientific Model Development	Downscaling land use and land cover from the Global Change Assessment Model for coupling with Earth system models
Leclère, D., Obersteiner, M., et al.	2020	Nature	Bending the curve of terrestrial biodiversity needs an integrated strategy
Lucas, P.L., Vuuren, D.P., Olivier, J.G.J., Elzen, M.G.J.	2007	Environmental Science & Policy	Long-term reduction potential of non-CO2 greenhouse gases
Maire, J., Alexander, P., Anthoni, P., Huntingford, C., Pugh, T.A.M., Rabin, S., Rounsevell, M., Arneth, A.	2022a	Springer International Publishing	A New Modelling Approach to Adaptation-Mitigation in the Land System
Maire, J., Sattar, A., Henry, R., Warren, F., Merkle, M., Rounsevell, M., Alexander, P.	2022b	Lancet Planetary Health	How different COVID-19 recovery paths affect human health, environmental sustainability, and food affordability: a modelling study
Mason-D'Croz, D., Bogard, J.R., Herrero, M., Robinson, S., Sulser, T.B., Wiebe, K., Willenbockel, D., Godfray, H.C.J.	2020	Nature Food	Modelling the global economic consequences of a major African swine fever outbreak in China
Mason-D'Croz, D., Bogard, J.R., Sulser, T.B., Cenacchi, N., Dunston, S., Herrero, M., Wiebe, K.	2019a	Lancet Planet Health	Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study
Mason-D'Croz, D., Sulser, T.B., Wiebe, K., Rosegrant, M.W., Lowder, S.K., Nin-Pratt, A., Willenbockel, D., Robinson, S., Zhu, T., Cenacchi, N., Dunston, S., Robertson, R.D.	2019b	World Development	Agricultural investments and hunger in Africa modeling potential contributions to SDG2 – Zero Hunger
Mauser, W., Klepper, G., Zabel, F., Delzeit, R., Hank, T., Putzenlechner, B., Calzadilla, A.	2015	Nature Communications	Global biomass production potentials exceed expected future demand without the need for cropland expansion
Merfort, L., Bauer, N., Humpenöder, F., Klein, D., Strefler, J., Popp, A., Luderer, G., Kriegler, E.	2023	Nature Climate Change	Bioenergy-induced land-use-change emissions with sectorally fragmented policies
Mittenzwei, K., Fjellstad, W., Dramstad, W., Flaten, O., Gjertsen, A.K., Loureiro, M., Prestegard, S.S.	2007	Ecological Indicators	Opportunities and limitations in assessing the multifunctionality of agriculture within the CAPRI model
Molotoks, A., Stehfest, E., Doelman, J., Albanito, F., Fitton, N., Dawson, T.P., Smith, P.	2018	Global Change Biology	Global projections of future cropland expansion to 2050 and direct impacts on biodiversity and carbon storage
Moore, F.C., Baldos, U., Hertel, T., Diaz, D.	2017	Nature Communications	New science of climate change impacts on agriculture implies higher social cost of carbon

Author	Year	Journal	Title
Nelson, G.C., Valin, H., et al.	2014	Proceedings of the National Academy of Sciences	Climate change effects on agriculture: Economic responses to biophysical shocks
Niazi, H., Wild, T.B., Turner, S.W.D., Graham, N.T., Hejazi, M., Msangi, S., Kim, S., Lamontagne, J.R., Zhao, M.	2024	Nature Sustainability	Global peak water limit of future groundwater withdrawals
Ohashi, H., Hasegawa, T., Hirata, A., Fujimori, S., Takahashi, K., Tsuyama, I., Nakao, K., Kominami, Y., Tanaka, N., Hijioka, Y., Matsui, T.	2019	Nature Communications	Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation
Osendarp, S., Akuoku, J.K., Black, R.E., Headey, D., Ruel, M., Scott, N., Shekar, M., Walker, N., Flory, A., Haddad, L., Laborde, D., Stegmuller, A., Thomas, M., Heidkamp, R.	2021	Nature Food	The COVID-19 crisis will exacerbate maternal and child undernutrition and child mortality in low- and middle-income countries
Patel, P., Edmonds, J., Kim, S., Zhao, X., Sheng, D., Waldhoff, S., Lochner, E.	2023	NA	Core Model Proposal# 332: GCAM Macro-Economic Module (KLEM Version)
Philippidis, G., Bartelings, H., Helming, J., M'barek, R., Smeets, E., Meijl, H.	2019	Economic Systems Research	Levelling the playing field for EU biomass usage
Philippidis, G., Ferrer-Pérez, H., Gracia-de-Rentería, P., M'Barek, R., Sanjuán López, A.I.	2021	Resources, Conservation and Recycling	Eating your greens: a global sustainability assessment
Philippidis, G., Shutes, L., M'Barek, R., Ronzon, T., Tabeau, A., Meijl, H.	2020	Journal of Cleaner Production	Snakes and ladders: World development pathways' synergies and trade-offs through the lens of the Sustainable Development Goals
Popp, A., Rose, S.K., Calvin, K., Van Vuuren, D.P., Dietrich, J.P., Wise, M., Stehfest, E., Humpenöder, F., Kyle, P., Van Vliet, J., Bauer, N., Lotze-Campen, H., Klein, D., Kriegler, E.	2014	Climatic Change	Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options
Potopová, V., Musiolková, M., Gaviria, J.A., Trnka, M., Havlík, P., Boere, E., Trifan, T., Muntean, N., Chawdhery, M.R.A.	2023	Agriculture	Water Consumption by Livestock Systems from 2002–2020 and Predictions for 2030–2050 under Climate Changes in the Czech Republic
Rabin, S.S., Alexander, P., Henry, R., Anthoni, P., Pugh, T.A.M., Rounsevell, M., Arneth, A.	2020	Earth Syst. Dynam.	Impacts of future agricultural change on ecosystem service indicators
Ramos, R.G., Scarabello, M.d.C., Costa, W., Andrade, P.R., Soterroni, A., Ramos, F.M.	2023	International Journal of Geographical Information Science	A mathematical programming approach for downscaling multi-layered multi-constraint land-use models
Ringler, C., Willenbockel, D., Perez, N., Rosegrant, M., Zhu, T., Matthews, N.	2016	Journal of Environmental Studies and Sciences	Global linkages among energy, food and water: an economic assessment
Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., Hausfather, Z., Havlík, P., House, J., Nabuurs, G.-J., Popp, A., Sánchez, M.J.S., Sanderman, J., Smith, P., Stehfest, E., Lawrence, D.	2019	Nature Climate Change	Contribution of the land sector to a 1.5 °C world

Author	Year	Journal	Title
Roelfsema, M., Soest, H.L., et al.	2020	Nature Communications	Taking stock of national climate policies to evaluate implementation of the Paris Agreement
Rosegrant, M.W., Sulser, T.B., Dunston, S., Mishra, A., Cenacchi, N., Gebretsadik, Y., Robertson, R., Thomas, T., Wiebe, K.	2024	Global Food Security	Food and nutrition security under changing climate and socioeconomic conditions
Rosegrant, M.W., Zhu, T., Msangi, S., Sulser, T.	2008	Review of Agricultural Economics	Global Scenarios for Biofuels: Impacts and Implications
Schmitz, C., Meijl, H., Kyle, P., Nelson, G.C., Fujimori, S., Gurgel, A., Havlik, P., Heyhoe, E., Croz, D.M., Popp, A., Sands, R., Tabeau, A., Mensbrugghe, D., Lampe, M., Wise, M., Blanc, E., Hasegawa, T., Kavallari, A., Valin, H.	2013	Agricultural Economics	Land-use change trajectories up to 2050: insights from a global agro-economic model comparison
Smeets Křístková, Z., Cui, H.D., Rokicki, B., M'Barek, R., Meijl, H., Boysen-Urban, K.	2025	Renewable and Sustainable Energy Reviews	European green bonds, carbon tax and crowding-out: The economic, social and environmental impacts of the EU's green investments under different financing scenarios
Snyder, A., Calvin, K.V., Phillips, M., Ruane, A.C.	2019	Geoscientific Model Development	A crop yield change emulator for use in GCAM and similar models: Persephone v1.0
Spillias, S., Valin, H., Batka, M., Sperling, F., Havlík, P., Leclère, D., Cottrell, R.S., O'Brien, K.R., McDonald-Madden, E.	2023	Nature Sustainability	Reducing global land-use pressures with seaweed farming
Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W.	2018	Nature	Options for keeping the food system within environmental limits
Springmann, M., Freund, F.	2022	Nature Communications	Options for reforming agricultural subsidies from health, climate, and economic perspectives
Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H.C.J., Gollin, D., Rayner, M., Ballon, P., Scarborough, P.	2016	The Lancet	Global and regional health effects of future food production under climate change: a modelling study
Stehfest, E., Bouwman, L., van Vuuren, D.P., den Elzen, M.G.J., Eickhout, B., Kabat, P.	2009	Climatic Change	Climate benefits of changing diet
Stehfest, E., Vuuren, D., Bouwman, L., Kram, T.	2014	Netherlands Environmental Assessment Agency (PBL)	Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications
Thomson, A.M., Kyle, G.P., Zhang, X., Bandaru, V., West, T.O., Wise, M.A., Izaurralde, R.C., Calvin, K.V.	2014	Global Environmental Change	The contribution of future agricultural trends in the US Midwest to global climate change mitigation
Valin, H., Sands, R.D., Mensbrugghe, D., Nelson, G.C., Ahammad, H., Blanc, E., Bodirsky, B., Fujimori, S., Hasegawa, T.,	2013	Agricultural Economics	The future of food demand: understanding differences in global economic models

Author	Year	Journal	Title
Havlik, P., Heyhoe, E., Kyle, P., Mason-D'Croz, D., Paltsev, S., Rolinski, S., Tabeau, A., Meijl, H., Lampe, M., Willenbockel, D.			
van den Bos Verma, M., Koch, S., Bartelings, H., van den Burg, S.	2023	Wageningen Economic Research, The Netherlands	The macro-economic effects of increasing seaweed production in the North Sea Region
Van Ha, P., Kompas, T., Nguyen, H.T.M., Long, C.H.	2017	Economic Modelling	Building a better trade model to determine local effects: A regional and intertemporal GTAP model
van Meijl, H., Havlik, P., Lotze-Campen, H., Stehfest, E., Witzke, P., Domínguez, I.P., Bodirsky, B.L., van Dijk, M., Doelman, J., Fellmann, T., Humpenöder, F., Koopman, J.F.L., Müller, C., Popp, A., Tabeau, A., Valin, H., van Zeist, W.-J.	2018	Environmental Research Letters	Comparing impacts of climate change and mitigation on global agriculture by 2050
van Meijl, H., Shutes, L., Valin, H., Stehfest, E., van Dijk, M., Kuiper, M., Tabeau, A., van Zeist, W.-J., Hasegawa, T., Havlik, P.	2020a	Global Food Security	Modelling alternative futures of global food security: Insights from FOODSECURE
van Meijl, H., Tabeau, A., Stehfest, E., Doelman, J., Lucas, P.	2020b	Environmental Research Communications	How food secure are the green, rocky and middle roads: food security effects in different world development paths
van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., van Meijl, H., Müller, C., van Ruijven, B.J., van der Sluis, S., Tabeau, A.	2017	Global Environmental Change	Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm
von Jeetze, P.J., Weindl, I., Johnson, J.A., Borrelli, P., Panagos, P., Molina Bacca, E.J., Karstens, K., Humpenöder, F., Dietrich, J.P., Minoli, S., Müller, C., Lotze-Campen, H., Popp, A.	2023	Nature Communications	Projected landscape-scale repercussions of global action for climate and biodiversity protection
von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason d'Croz, D., Nelson, G.C., Sands, R.D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., van Meijl, H.	2014	Agricultural Economics	Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison
Walsh, M.J., Gerber Van Doren, L., Sills, D.L., Archibald, I., Beal, C.M., Lei, X.G., Huntley, M.E., Johnson, Z., Greene, C.H.	2016	Environmental Research Letters	Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency
Wang, Z., Martha, G., Liu, J., Lima, C., Hertel, T. W.	2024	Science of The Total Environment	Planned expansion of transportation infrastructure in Brazil has implications for the pattern of agricultural production and carbon emissions
Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., Mensbrugghe, D., Biewald, A., Bodirsky, B., Islam, S., Kavallari, A., Mason-D'Croz, D., Müller, C., Popp, A., Robertson, R., Robinson, S., Meijl, H., Willenbockel, D.	2015	Environmental Research Letters	Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios

Author	Year	Journal	Title
Willett, W., Rockström, J., et al.	2019	The Lancet	Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems
Wise, M., Muratori, M., Kyle, P.	2017	Transportation Research Part D: Transport and Environment	Biojet fuels and emissions mitigation in aviation: An integrated assessment modeling analysis
Wilts, R., Latka, C., Britz, W.	2021	Climate Risk Management	Who is most vulnerable to climate change induced yield changes? A dynamic long run household analysis in lower income countries
Zeng, Y., Rao, Y., Xu, Z.	2023	The International Journal of Health Planning and Management	Anticipated cancer burden of low individual fruit and vegetable consumption under climate change: A modelling study in China
Zhao, M., Wild, T.B., Graham, N.T., Kim, S., Binsted, M., Chowdhury, A.F.M.K., Msangi, S., Patel, P.L., Vernon, C.R., Niazi, H., Li, H.Y., Abeshu, G.W.	2023	Geoscientific Model Development Discussions	GCAM-GLORY v1.0: Representing Global Reservoir Water Storage in a Multisector Human-Earth System Model
Zhao, X., Mignone, B.K., Wise, M.A., McJeon, H.C.	2024	Nature Communications	Trade-offs in land-based carbon removal measures under 1.5 °C and 2 °C futures
Zhao, X., Wise, M.A., Waldhoff, S.T., Kyle, G.P., Huster, J.E., Ramig, C.W., Rafelski, L.E., Patel, P.L., Calvin, K.V.	2022	Global Environmental Change	The impact of agricultural trade approaches on global economic modeling

Appendix C

This is a list of various models not included in the evaluation presented in Section 3, yet they remain valuable tools for analysing food systems.

Partial Equilibrium (PE) Models

GAPS: The Global Agriculture Perspectives System (GAPS) model is a partial equilibrium model developed by the Food and Agriculture Organisation (FAO) that includes 34 crop and 4 livestock activities (*227*).

Computable General Equilibrium (CGE) Models

ENVISAGE: The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model focuses on the interactions between the economy and the environment, with detailed agricultural and land-use components, developed by the World Bank (*228*).

EPPA: Emissions Prediction and Policy Analysis (EPPA) is a CGE model used to project economic activity, energy use and greenhouse gas (GHG) emissions for 12 wolrd regions through the year 2100 developed by the Massachusetts Institute of Technology (*229, 230*).

FARM: The Future Agricultural Resources Model (FARM) is a global CGE model with particular focus on agriculture, forestry and energy sectors, developed by the United States Department of Agriculture (USDA) (*231*).

Input-Ouput Models

MRIO: The model is designed to track financial and quantity flows between countries and major economic sectors, including agriculture and food (e.g., (*232*)).

FABIO: The Food and Agriculture Biomass Input–Output model (FABIO), a set of multiregional supply, use and input–output tables in physical units, that document the complex flows of agricultural and food products in the global economy (*233*).

AMRIO: Adaptive Multi-Regional Input–Output (AMRIO) models were developed to overcome limitations of MRIO on the lack of flexibility in the economic system and the inability to assess the consequence of a shock on the supply side (*234*), and have been applied to assess disruptions in global food supply chains (*235*).

Biophysical process model

GLEAM: The Global Livestock Environmental Assessment Model (GLEAM) was developed by the FAO to enable the quantification of greenhouse gases emissions arising from the production of the 11 main livestock commodities globally at a spatial resolution of 0.05 decimal degrees (*236, 237*).

BIOSPACS: The Balancing Inputs and Outputs for the Sustainable Production of Agricultural CommoditieS (BIOSPACS) is a model developed to quantify nitrogen and phosphorus flows between five interacting components in the food system and those across the system's boundary as a function of food demand (*238*)

BioBaM: The Biomass Balance Model (BioBaM) is a biophysical accounting model that calculates the balance between biomass supply and biomass demand at the level of 11 world regions, for 14 biomass demand categories and corresponding primary commodities (*43, 239-241*).

SOL-model: The SOL-model is a bottom-up, mass-flow model of agricultural production and the food sector (*42, 242*).

FALAFEL: The Flux Assessment of Linked Agricultural Food production, Energy potentials and Land-use change (FALAFEL) (*243*) and its successor, the Country-Level Land Availability Model for Agriculture (C-

LLAMA) (*244*) model, are bottom-up models using linear projections of global food supply, agricultural efficiencies, and yields to produce trajectories for land use, carbon capture based on FAOSTAT database. The model can explore scenarios up to 2050.

Others

We list below other types of modelling frameworks using different approaches from partial and general equilibrium integrated assessment and input-output models.

Food circularity optimisation, such as *CiFoS*: Circular Food Systems (CiFoS) is a biophysical data-driven food system optimization model that accounts for the potential to use natural processes and cycles to ensure that waste or by-products from one process form the input of another process (*114*).

System dynamics, such as *FeliX:* The Full of Economic-Environment Linkages and Integration dX/dt (FeliX) is a system dynamics model of global social, economic, and environmental Earth systems (*116, 245*).

Multi-objective optimisation, such as *MOO-GAPS* is a multi-objective optimisation model that aims to optimise more than one objective when assessing different options of land use allocation. This type of model can be used to assess the frontier of pareto-efficient land use to produce food and quantify trade-offs between multiple objectives with a particular focus on beef production (*46*).

Agricultural and land use accounting model, such as *FABLE Calculator*: The food, agriculture, biodiversity, land, and energy (FABLE) Calculator is an integrated model designed to help overcome technical and cost requirement barriers related to existing integrated assessment models. It is an open-source, Excel-based food and land-use system assessment tool, that is relatively easy to learn and use yet complex enough to provide reasonable estimates of multi-objective impacts (*33, 132, 182*).

LCA: life cycle assessments aim to quantify the total impacts of a product, in this case food commodities, throughout the entire life cycle (*246, 247*).

Physical trade flows: Physical trade flow models calculate impacts of food production and consumption considering trade flows based on trade matrices (*248, 249*).

Mass-balance model: Mass-balance models can be used to assess impacts of a specific aspect of the food system (*250, 251*), e.g., food loss and waste, and explore intervention scenarios.

Regression-based model: Changes in the food system over time, for instance plant-based and animal-based calorie demand, can be simulated using time-dependent regression models (*41*).

Multi-models or ensemble models: The use of multiple models, some of which have been described above, whereby simulations are run independently but with the same scenario settings is increasingly used to capture some of the uncertainty pertaining to using different modelling approaches and to provide an envelope of model projections (*7, 84, 201, 252, 253*)

Appendix D

Table D1. Description of dimensions used to compare models in Table 1 (main text).

Dimension	Description
Health impacts of diets	Evaluation of impacts of different diets on human health
Average food affordability	Simulation on the change in food affordability, accounting for price of food commodities, and available income or wage.
Undernourishment	Simulation of sufficiency of minimum requirements of dietary energy and food quality
Employment	Consideration of the impact of the agrifood system on employment.
Trade	Simulation of the trade of agricultural products
Economic return	The extent to which economic returns from agricultural production are modelled
Emissions	Emissions from the food system that can be simulated
Biodiversity loss	The assessment of the impact of the food system on biodiversity
Water resource use	The extent to which water resources, including water demand and availability of surface and groundwater, are simulated in the model
Biogeochemical flow	The extent to which flows and cycles of nutrients (e.g., nitrogen and phosphorus) are simulated
Technology/practice (AFOLU measures)	The Agriculture, Forestry and Land Use (AFOLU) measures to mitigate GHG emissions that can be considered
Demographics	Simulation of population change and its impacts on the food system
GDP	Inclusion of GDP and its relation to the food system
Food demand	The extent to which models simulate the current and future food demand endogenously
Agrifood and climate Policies	Policies and economic instruments, e.g., agricultural subsidies and taxes, that can be simulated
Land-use change	The simulation of land use change and land use intensity
Bioenergy supply	The types of bioenergy feedstocks that are modelled (e.g., 1^{st}, 2^{nd} and 3^{rd} generation)
Chronic climate change impacts	The inclusion of various long-term climate change (change in temperature, precipitation, drought, flooding) impacts on and their effect on agriculture (yield, heat stress, supply chain disruptions)
Acute shocks	The extent to which acute shocks, such as extreme climate events, pandemics or economic conflicts are simulated
Maturation of technology/innovation	The extent to which models endogenously represent the drivers of learning curves, technological advancements, and associated cost reductions in models
Vested interests and coalitions	The extent to which models internally represent the political economy of change, including the vested interests of powerful actors and their coalitions, which either foster or resist transformation
Primary production	Number of primary or raw agricultural products are included
Aquaculture and fisheries commodities	Number of aquaculture and wild catch fisheries commodities included
Domestic transport and storage	The endogenous modelling of logistics and distribution network, including transport, storage, and delivery
Processed food commodities	Number of processed food commodities are included
Demand shift	Simulation of changes in food demand and diet shifts
Novel food and feed	The consideration of novel food (e.g., cultured meat) and feed (e.g., seaweed additive in feed) and their impacts on substitution
Waste and loss	Assessment of food waste and loss for different types of food, and its impact on the food system

Table D2. Justification and supporting references for the assessment of models provided in Table 1 (main text).

Dimension	**Partial equilibrium models** (i.e., AgLINK-COSIMO, CAPRI, GLOBIOM, IMPACT, MAgPIE, SIMPLE-G)	**General equilibrium models** (i.e., AIM, CGEBox, DART-BIO, GTAP, GTEM, MAGNET, MIRAGRODEP)	**Integrated assessment models** (GCAM and IMAGE)	**Coupled models** (i.e., GLOBE-IMPACT, LandSyMM, IMAGE-MAGNET, MESSAGEix-GLOBIOM, REMIND-MAgPIE)
Sustainability outcomes				
Health impacts of diets	**A-E** | Most models do not simulate health impacts explicitly, however MAgPIE has been used to project the change in food consumption on body mass index and obesity (*9, 254, 255*). IMPACT has been linked to health models to simulate macronutrient and caloric intake (kcal/day) for the EAT Lancet recommendations (*9*) and anticipated disease burden of low individual fruit and vegetable consumption (*206, 255*)	**E** |Models have not been used yet to assess health impacts of diets but MAGNET has been linked to an health model to assess health impacts of removing agricultural subsidies (Springmann and Freund 2022)	**E**| Models have not been used yet to assess the health impacts of diets	**A-E** | Health impacts have been simulated using LandSyMM modelling framework (*256, 257*) and can be simulated through model coupling, e.g., with IMPACT and MAgPIE
Average food affordability	**A-C**| Food prices are simulated but no simulation of total household income (*258*)	**A-E** | Food affordability can be simulated by considering availability, price, consumption, per capita food expenditure and welfare at country level for instance in MAGNET (*85, 259*) and MIRAGRODEP (*63*)	**C-E**| Food prices are simulated but household income and wages are exogenous (*260*)	**A** | Food affordability could be simulated via coupled PE and CGE models, GLOBE and IMPACT (*261*) and with LandSyMM modelling framework (*257*)
Undernourishment	**A-E** | Most models have been used to simulate nutrient availability. CAPRI, GLOBIOM, IMPACT and MAgPIE have been used to simulate various indicators of food security, including calorie availability and number of people at risk of hunger (*84*). IMPACT has been used to simulate future average food supply and population at risk of hunger (*225, 262*). Aglink-cosimo has been used to model food calories per capita (*263*)	**A-E** | Scenarios of future risk of hunger have been explored with AIM (*264*) and MAGNET using calorie intake per person per day (*265*). MIRAGRODEP has been used to link the COVID-19 pandemic with changes in income and the impact on diets (*266*)	**A** | Scenarios of future changes in dietary energy availability have been explored with GCAM and IMAGE using calorie intake per person per day (*84*)	**A** | Risk of hunger can be simulated**,** for instance by coupling GLOBE and IMPACT models (*262*), or via IAMs (*253*)
Employment	**A-E**| Only MAgPIE considers the number of people employed in crop and livestock production (*267*)	**A**| employment impacts of changes in the food system can be investigated, e.g., with MAGNET model (*268*)	**B-E**| Labor force participation rate and Labor productivity growth rate are exogenous variables (*260*)	**A-E** | Coupled CGE models, e.g., GLOBE, can simulate labour force (*261*)
Trade	**A** | Trade of agricultural products is simulated either as net trade, for instance in IMPACT, or bilateral trade flows are simulated based on cost competitiveness and homogeneous good assumption. Tariffs and trade costs (e.g., CIF) are considered (*269, 270*)	**A**| Models include detailed representation of global trade across all sectors of the economy and are often used to assess the impacts of trade policies or trade disruptions on the economy (*36*)	**A-E**| International trade can be simulated by one of two methods: (1) Heckscher-Ohlin (single global markets), or (2) Armington Style Trade (global trade with regionally-differentiated markets with Armington-like preferences between domestic and imported commodities) (*271*). IMAGE requires coupling with MAGNET to simulate trade.	**A** | Coupled CGE and PE models can simulate trade in agriculture and other economic sectors (*224*)
Economic return	**A-C**| Economic returns in the agricultural sector can be simulated from agricultural production and prices (*258*)	**A**| Value of production in all sectors of the economy is simulated and change in	**A-E**| Profit is used to determine decisions in the land system based on logit formulation (*64*)	**A-E** | Changes in income can be simulated via coupled PE and/or CGE models (*258*)

		household income can be evaluated (*272*)		
Emissions	**A** | All models simulate emissions from agriculture although some models do not account for land use change emissions, e.g., IMPACT.	**A**| Coverage of emissions in all sectors of the economy but land-based negative emissions are captured exogenously or at aggregated spatial scales, unless coupled with a spatially explicit land use model, e.g., AIM-CGE (*273*). CGEBox calculates carbon stock changes at AEZ level (*274*).	**A**| Comprehensive coverage of emissions in all sectors of the economy including the land sector at regional level in GCAM (*275*). IMAGE includes all AFOLU emissions (*94*)	**A** | Coupled models can simulate emissions in agriculture, land use and other sectors of the economy (*276*)
Biodiversity loss	**A-E** | Land use change can be linked to biodiversity indices, e.g., Biodiversity Intactness Index (BII) in GLOBIOM and MAgPIE (*201*)	**A-E** | AIM has been used to model biodiversity indices, e.g., BII (*201*) and vertebrate species loss as a result of land-based mitigation (*277*). Similar for CGEBox in Goebel and Britz (*278*).	**A-E** | IMAGE has been used to assess impacts of land use change on species habitats and BII (*201*) and loss of biodiversity hotspots (*279*)	**A-E** | Coupled models can simulate biodiversity from land use change via coupled PE or IAM model (*201*). MAgPIE has been coupled with an ecosystem service model (*280*)
Water resource use	**A-E**| Water footprint from irrigation and livestock consumption is considered in GLOBIOM (*281*). IMPACT includes a global hydrology model (IGHM) that simulates runoff, crop water allocation and stress spatially (*261*)	**A-E**| Most models do not simulate water resource use from agriculture but some models differentiate between irrigated and rainfed agricultural production, e.g., some versions of GTAP (*211, 282*) and CGEBox (*214*)	**A** | In IMAGE, the hydrological cycle is represented by linking with LPJmL (*283*). GCAM includes water markets and the impact of water prices on water supply (*284*)	**A** | Coupled models can be used to simulate water resource use from agriculture (*20, 218, 261*)
Biogeochemical flow	**A** | GLOBIOM has been used to quantify regional nitrogen surplus boundaries for different nitrogen mitigation options (*285*). MAgPIE has detailed Nitrogen (N) flow module (*286*).	**E** | Limited representation of biogeochemical flows.	**A** | IMAGE model has a detailed representation of nitrogen and phosphorus cycles (*287, 288*) whereas GCAM simulates N and P fertilizer production and use (*288, 289*)	**A** | Biogeochemical flows can be simulated via coupled PE models or vegetation models, e.g., LPJ-GUESS for IMAGE-MAGNET or LandSyMM (*222, 290*)
Drivers of change				
Technology / practice (AFOLU measures)	**A** | PE models, particularly CAPRI, GLOBIOM and MAgPIE have been used to simulate a large range of non-CO_2 agricultural emissions and land based mitigation measures (*7, 252, 291-294*). GLOBIOM has been used to simulate CO_2 mitigation measures on cropland (*295*). IMPACT has been used to model the effect of new crop technologies on the impact of climate change (*296*) however it does not simulate land-based mitigation.	**A-E** | AIM/CGE includes a range of mitigation options, including afforestation and BECCS (*159*). MAGNET has been used to simulate agricultural non-CO_2 emission reduction potential (*7*) but requires IMAGE to simulate LULUCF.	**A-B** | In GCAM, afforestation/reforestation, avoided deforestation, and BECCS are explicitly considered as AFOLU measures (*275*) and agricultural technologies can be simulated exogenously (*297*). Trend in agricultural technologies and the value of agricultural land use to inform afforestation in IMAGE are taken from MAGNET model (*298*).	**A-E** | Agricultural technologies and land-based mitigation measures can be simulated via coupled PE or CGE models (*299*)
Demographics	**B** | Population is considered exogenously as a driver of food demand (*258*).	**B** | Population is considered exogenously as a driver of food demand (*300*).	**B** | Population is considered exogenously as a driver of demand (*258*).	**B** | Population is considered exogenously as a driver of demand (*258*).
GDP	**B** | GDP is considered exogenously as a driver of food demand (*258*).	**A**| GDP can be simulated endogenously or included exogenously as a driver (*300, 301*)	**A-B** | GCAM v7 incorporates a macroeconomic module that allows for fully endogenizing GDP responses (*302*). IMAGE requires coupling with MAGNET to simulate GDP and its impact on food demand.	**A-B** | GDP can be simulated via a CGE model (e.g., REMIND, MAGNET, GLOBE) or a macro-economic model (MACRO) in the case of MESSAGEix-GLOBIOM (*218*). GDP is included exogenously in LandSyMM (*67*).

Food demand	**A**| Food demand is calculated endogenously, often considering income and price effects but with limited representation of other drivers, e.g., education, local traditions, degree of urbanization (*258*)	**A**| food demand is simulated based on utility functions using a variety of approaches, e.g., Linear Expenditure System (LES), constant-elasticity-of-substitution (CES) and Constant Differences in Elasticities (CDE) utility functions (*258, 303*)	**A-B** | GCAM has an exogenous trend in price elasticity depending on time (*258*) whereas IMAGE uses MAGNET outputs on food demand (*68*)	**A** | Food demand is simulated endogenously using partial equilibrium models (GLOBIOM, MAgPIE), CGE model (e.g., MAGNET) or a specialised food demand model (e.g., MAIDADS for LandSyMM) (*304*)
Policy	**A-B** | Most models can simulate policies as shocks, particularly carbon price, on agriculture (*84*). In addition, CAPRI and IMPACT have been used to simulate the impact of taxes on final meat and dairy products on emissions and health (*93, 305*). Aglink-COSIMO has been used to simulate trade policies, e.g., ban, quotas and taxes (*306*) and mandates, tax credits, import and export tariffs (*307*). CAPRI can simulate several policy instruments endogenously, such as subsidised exports, administrative stocks and tariffs (Britz and Witzke 2014).	**A** | Taxes (e.g., on carbon or processed food) can be modelled exogenously, e.g., in GTAP (*308*) and DART-BIO (*309*). Carbon price and emission trading scheme can be simulated endogenously, e.g., in AIM/CGE (*310*). Agricultural subsidies can be simulated with MIRAGRODEP (*311*) and MAGNET (*312*). Green investments, budget-neutrality and import tariffs can be simulated with MAGNET (*313, 314*). All CGE models capture tariffs, partly as very fine-grained resolution for agri-food such as in Jafari *et al.* (*315*).	**A-B** | Taxes, technology subsidies and emission/land constraints can be simulated in GCAM and carbon price can be simulated endogenously (*260, 316*). IMAGE considers policies exogenously from MAGNET model.	**A** | Models can simulate policies, including carbon price endogenously (*317*).
Land-use change	**A** | Most models simulate all major land uses endogenously and spatially (*152*). IMPACT model only assesses changes in agricultural and non-agricultural land uses. Aglink-Cosimo simulates land use change at regional level.	**A-E** | Most models include land use change at regional or country level. All major land uses can be simulated dynamically in AIM (*318*), and downscaled to obtain gridded land use at 50km resolution (*273, 319*). MAGNET requires coupling with IMAGE to model land use change.	**A** | Land use change can be simulated at grid level (50km) in the case of IMAGE (*150*) or regional level and downscaled to gridded level in the case of GCAM (*320*).	**A** | Land use change can be simulated via coupled PE or IAM model (*321*) or via land use model PLUMv2 for LandSyMM (*222*).
Bioenergy	**A**| First and second generation biofuels are considered in most models (*258, 322, 323*). The feedstock production is simulated endogenously but the demand is exogenous in most models, except Aglink-Cosimo, which simulates demand for biofuels endogenously (*324*). Biofuel from seaweed and forestry residues can also simulated exogenously (*325*).	**A-E**|Demand for first and second generation biofuels is considered endogenously in AIM (*300, 326*), GTAP (*327*), MIRAGRODEP (*328*) and DART-BIO (*329*). Bioenergy and other applications from biomass resources are often captured through splitting up the GTAP database, for instance to asses bio-plastics (Escobar et al. 2018)	**A** |First and second generation biofuels are modelled, as well as biofuel from seaweed and forestry residues in GCAM (*321, 330, 331*). IMAGE simulates first and second generation bioenergy potential and demand (*321, 332*).	**A-B** | Bioenergy supply and demand can be modelled endogenously, e.g., in REMIND-MAgPIE and IMAGE framework (*65, 333*) but demand is exogenous in LandSyMM (*222*).
Climate change impacts	**B** | Climate change impacts on agricultural productivity are considered exogenously through the impacts on crop and animal yields using gridded vegetation models such as EPIC and LPJML (*252, 334-336*).	**B-E** | Climate change impacts on productivity at the country level is considered through climate damage functions in GTAP (*337*) or by using aggregated crop yield projections, e.g., LPJmL or M-GAEZ (*338*). CGEBox has been used to assess climate change-induced yield changes on welfare of household groups (*339*).	**B** |Climate change impacts of productivity is considered through the impacts on crop yields using gridded vegetation models such as LPJML for IMAGE (*65*). Impacts of climate change on crop yields can be simulated at regional level (*340*) or taken from a yield response emulator to evaluate dynamic yield responses to a climate event, e.g., multi-year drought (*341*) in GCAM.	**A-B** | Coupled models can simulate climate change impacts on agriculture endogenously, e.g., using sub-models IMOGEN in landSYMM (*342*) and MAGICC in IMAGE, MESSAGEix-GLOBIOM and REMIND-MAgPIE frameworks (*65, 218, 343*).
Acute shocks	**B-E** | IMPACT model has been used to simulate the economic impacts of a plant disease outbreak (*344*). Aglink-Cosimo	**B-E** | Some models, e.g., MIRAGRODEP, have been used to analyse the impact of pandemics on global poverty,	**B-E** | GCAM can be coupled with specialised models to assess the	**B-E** | GLOBE and IMPACT models have been linked to simulate the impacts of an African swine fever outbreak in

	was used to assess the impacts of climate extremes using the combined stress index proxy on the global food system (*345*) and the impacts of the COVID-19 pandemic on the global agricultural markets (*346*).	food security and diets (*266, 347*). AIM/CGE was used to examine the effects of extreme climate events on the future risk of hunger (*348*).	impacts of drought on the economy (*341, 349*)	China on food system dynamics (*224*). LandSyMM was used to assess human health, environmental sustainability, and food affordability following the COVID-19 (*257*).
Maturation of technology/innovation	**B** | Uptake of agrifood technologies is based on economic viability (*292*) and marginal abatement cost curves (*291*).	**C-E** |MAGNET includes technology learning rates (*314*).	**C** | Technical mitigation in the agricultural sector is implemented through MAC curves as implemented in the climate policy submodel of IMAGE (*350*).	**B-C** | Uptake of agrifood technologies could be represented via coupled PE and CGE models.
Vested interests and coalitions	**E** | Not represented in current models	**E** | Not represented in current models	**E** | Not represented in current models	**E** | Not represented in current models
Primary production	**A** | The major primary crop (16-26) and livestock (5-6) products. IMPACT includes 26 crops (*258*), CAPRI includes 32 crops, 5 fodder products and 9 marketable animal products (*351*). Aglik-Cosimo covers over 90 commodities (*352*).	**A** | Most models include between 6 (AIM) and 12 (GTAP) commodities and the main livestock products (ruminant meat, milk and other meat) (*258*). Britz (*83*) dis-aggregates the GTAP data base to cover 40 primary agricultural products.	**A** | GCAM includes 15 crop and 6 livestock commodities (*258, 260*), IMAGE includes 16 crop and 4 livestock products (*159*).	**A** | Same representation as in coupled models
Aquaculture and fisheries commodities	**A-E** | Not included in main food product but the model can be adapted to explore scenarios of marine product consumption (*325*). AGLINK–COSIMO includes "fish and aquaculture", "fish meal" and "fish oil" as commodities and has been linked to the FAO Fish model for more detailed representation of fisheries commodities (*353*).	**A-E** | Some models, e.g., GTAP have limited representation of fisheries, included in one aggregated commodity with hunting and trapping. However other models, e.g., DART-BIO (*354*) and MAGNET (*355*) have a detailed fisheries, aquaculture and seaweed sector.	**E** | Limited representation of aquaculture and fisheries.	**A-E** | Same representation as in coupled models.
Domestic transport and storage	**C-E** | MAgPIE simulates the intraregional transportation of agricultural products between producer site and the next city centre (market) (*267*). CAPRI includes some storage and transport costs, e.g., seed and manure (*51*). SIMPLE-G was used to simulate the implications of an expansion of transportation infrastructure of agricultural production in Brazil (*356*).	**D-E** | Not included.	**A-E** | Agricultural stockholding behaviour is included in GCAM as a technology whereby regional consumers can allocate regional supply to current consumption or future consumption for 13 crop commodities (*260*).	**E |** Not included.
Processed food commodities	**A-E** | A version of GLOBIOM includes vegetable oil as a commodity (*357*), whereas IMPACT and CAPRI include 8 and 28 processed commodities, respectively (*252, 258*). Aglink-Cosimo includes a large range of processed commodities including oilseeds products, sugars and sweeteners, dairy products and fish meal and oil (OECD-FAO 2022).	**A** | Ranging from 1-16 commodities (*258*). DART-BIO includes 16 processed agricultural products (*358*). MAGNET includes the same commodities as the included in the GTAP database, in addition to crude vegetable oil.	**E** | Not included.	**A-E** | Same representation as coupled models. LandSyMM does not include food processing (*257*).
Demand shift	**B-E** | IMPACT model has been used to inform diet shifts based on environmental and health impacts for the EAT Lancet (*9, 208*). Dietary changes are	**B-E** | Diet shifts and calorie intake can be modelled exogenously using CGE models such as MAGNET (*85*).	**B-E** | Diet shifts and multiple impacts on sustainability have been investigated with GCAM (*289*) and IMAGE (*94*).	**B** | Same representation as in coupled PE and CGE models. LandSyMM models shifts in food demand via MAIDADS sub-model (*257*).

	generally implemented exogenously.			
Novel food and feed	**B-E** | Models have been used to assess the impacts of innovation on the food system, for instance replacing beef with microbial protein with MAgPIE (*359*), introducing seaweed for food and feed (GLOBIOM) (*325, 360*). Aglink-Cosimo has been used to model the use of insects reared on food waste for feed and fuel (*361*).	**A-E** | MAGNET has been used to simulate the uptake of low-cost feed derived from by-products and agricultural residues endogenously based on agricultural policies (*313*).	**E** | Not included.	**A-E** | Adoption of novel food or feed could be represented via coupled PE (e.g., GLOBIOM and MAgPIE) and CGE models (e.g., MAGNET).
Waste and loss	**B** | Food waste and loss are included explicitly as exogenous variable for different food types (*93, 205, 361, 362*).	**B-E** | Most models include food loss and waste exogenously (*268, 363-365*).	**D-E** | Food waste is captured implicitly in GCAM by adjusting meat consumption and preferences in different SSPs (*260*).	**B-D** | Same representation as coupled models. LandSyMM only represents food loss in transport (*222*).
Other model details				
Spatial resolutions	Most models simulate land use change and agricultural production spatially, except Aglink-Cosmo. Spatial resolution of agricultural production varies between ~50km resolution (GLOBIOM and MAgPIE) (*152*). Downscaling algorithms have been use to disaggregated outputs of GLOBIOM (*366*) and CAPRI (*124*) to 1km resolution, and MAgPIE has been used in combination with SEALS to downscale land cover at ~300m resolution (*366, 367*).	Supply units tend to be aggregated at country or country-AEZ level. Some models, e.g., AIM/CGE have downscaling algorithms to allocate some variables, e.g., land use, from 17 aggregated AEZ regions to 50 km grid (*152, 368*). CGEBox can depict sub-national units (for instance, Jafari et al. 2020) including sub-national households with subsistence production (*369*).	Land use change can be simulated at high resolution (~10km) in the case of IMAGE or regional level in the case of GCAM. Downscaling algorithms, e.g., DEMETER can be used to obtain gridded land use at fine spatial resolution (10km) (*152, 320, 370*) and GLOBIO for IMAGE land use results (300m).	
Temporal dimension	Annual to 10-year time step, with time horizon from 10 years in the future (Aglink Cosmo) to 2100 (e.g., GLOBIOM, MAgPIE). Most models are dynamic except CAPRI and SIMPLE-G, which are comparative static.	Most CGE models are dynamic and can provide results at annual time step until 2100. Some variations of GTAP can be solved in a comparative static (Hertel et al., 2010), recursive dynamic (*214*) or intertemporal framework (*371*) and MIRAGRODEP can used in a comparative static or recursive dynamic approach (*372*)	5 year time step until 2100 for GCAM (*64*) and annual time step until 2100 for IMAGE (*65*).	Between annual (e.g., IMAGE-MAGNET) and 10 year time steps (MESSAGEix-GLOBIOM) up to 2100 in most cases.

REFERENCES

1. R. Bandari *et al.*, Participatory Modeling for Analyzing Interactions Between High-Priority Sustainable Development Goals to Promote Local Sustainability. *Earth's Future* **11**, e2023EF003948 (2023).
2. F. Gaupp *et al.*, Food system development pathways for healthy, nature-positive and inclusive food systems. *Nat. Food.* **2**, 928-934 (2021).
3. S. Cucurachi, L. Scherer, J. Guinée, A. Tukker, Life Cycle Assessment of Food Systems. *One Earth* **1**, 292-297 (2019).
4. J. von Braun, K. Afsana, L. O. Fresco, M. H. A. Hassan, Eds., *Science and Innovations for Food Systems Transformation*, (Springer Cham, Switzerland, 2023).
5. P. J. Ericksen, Conceptualizing food systems for global environmental change research. *Global Environ. Change* **18**, 234-245 (2008).
6. T. Allen, P. Prosperi, Modeling Sustainable Food Systems. *Environ. Manage.* **57**, 956-975 (2016).
7. S. Frank *et al.*, Agricultural non-CO2 emission reduction potential in the context of the 1.5 °C target. *Nat. Clim. Change.* **9**, 66-72 (2019).
8. L. Gao, B. A. Bryan, Finding pathways to national-scale land-sector sustainability. *Nature* **544**, 217 (2017).
9. W. Willett *et al.*, Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447-492 (2019).
10. S. W. D. Turner *et al.*, A pathway of global food supply adaptation in a world with increasingly constrained groundwater. *Sci. Total Environ.* **673**, 165-176 (2019).
11. B. Yarlagadda *et al.*, Trade and Climate Mitigation Interactions Create Agro-Economic Opportunities With Social and Environmental Trade-Offs in Latin America and the Caribbean. *Earth's Future* **11**, e2022EF003063 (2023).
12. S. Acs *et al.*, "Modelling for EU Policy support: Impact Assessments. EUR 29832 EN," (Publications Office of the European Union, Luxembourg, 2019). Retrieved from:
13. EPRS, "Revision of the Waste Framework Directive," (European Parliamentary Research Service, European Parliment, 2023). Retrieved from: https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/753168/EPRS_BRI(2023)753168_EN.pdf
14. EU, "Stepping up Europe’s 2030 climate ambition: Investing in a climate-neutral future for the benefit of our people," (European Commission, Directorate-General for Climate Action, 2020). Retrieved from: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52020SC0176
15. EPA, "Renewable Fuel Standard (RFS) Program: Standards for 2023–2025 and Other Changes," (Environmental Protection Agency, USA, 2023). Retrieved from: https://www.federalregister.gov/documents/2023/07/12/2023-13462/renewable-fuel-standard-rfs-program-standards-for-2023-2025-and-other-changes
16. A. S. Teeuwen, M. A. Meyer, Y. Dou, A. Nelson, A systematic review of the impact of food security governance measures as simulated in modelling studies. *Nat. Food.* **3**, 619-630 (2022).
17. B. Müller *et al.*, Modelling food security: Bridging the gap between the micro and the macro scale. *Global Environ. Change*, (2020).
18. P. M. Reed *et al.*, Multisector Dynamics: Advancing the Science of Complex Adaptive Human-Earth Systems. *Earth's Future* **10**, e2021EF002621 (2022).
19. S. Robinson *et al.*, The international model for policy analysis of agricultural commodities and trade (IMPACT): model description for version 3. (2015).
20. J. C. Doelman *et al.*, Quantifying synergies and trade-offs in the global water-land-food-climate nexus using a multi-model scenario approach. *Environ. Res. Lett.* **17**, 045004 (2022).
21. M. Pelling, *Adaptation to Climate Change: From Resilience to Transformation*. (Taylor & Francis, 2010).
22. C. Conti *et al.*, Complexity-aware principles for agri-food system interventions: Lessons from project encounters with complexity. *Agric. Syst.* **220**, 104080 (2024).
23. C. Allen, S. Malekpour, Unlocking and accelerating transformations to the SDGs: a review of existing knowledge. *Sustain. Sci.* **18**, 1939-1960 (2023).
24. F. H. Knight. (Houghton mifflin company, Boston, MA, 1921).
25. R. J. Lempert, S. W. Popper, S. C. Bankes, *Shaping the next one hundred years: new methods for quantitative, long-term policy analysis*. (Rand Corporation, 2003).
26. Y. Ben-Haim, *Info-Gap Decision Theory: Decisions Under Severe Uncertainty*. (Academic Press, London, UK, 2006).
27. J. M. Keynes, *A Treatise on Probability*. (Dover Publications, New York, USA, 1921).
28. K. Kabir, S. de Vries Robbe, C. Godinho, Climate change mitigation policies in agriculture: An overview of sociopolitical barriers. *WIREs Climate Change* **15**, e916 (2024).

29. M. D. A. Rounsevell *et al.*, Towards decision-based global land use models for improved understanding of the Earth system. *Earth Syst. Dynam.* **5**, 117-137 (2014).
30. M. Reilly, D. Willenbockel, Managing uncertainty: a review of food system scenario analysis and modelling. *Philosophical Transactions of the Royal Society B: Biological Sciences* **365**, 3049-3063 (2010).
31. L. Gao, B. A. Bryan, Incorporating deep uncertainty into the elementary effects method for robust global sensitivity analysis. *Ecological Modelling* **321**, 1-9 (2016).
32. S. Hatfield-Dodds *et al.*, Australia is ‘free to choose’ economic growth and falling environmental pressures. *Nature* **527**, 49-53 (2015).
33. J. Navarro Garcia *et al.*, Multi-target scenario discovery to plan for sustainable food and land systems in Australia. *Sustain. Sci.* **18**, 371-388 (2023).
34. J.-F. Mercure *et al.*, Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. *Global Environ. Change* **37**, 102-115 (2016).
35. A. Arneth, C. Brown, M. D. A. Rounsevell, Global models of human decision-making for land-based mitigation and adaptation assessment. *Nat. Clim. Change.* **4**, 550-557 (2014).
36. M. von Lampe *et al.*, Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agr. Econ.* **45**, 3-20 (2014).
37. I. Keppo *et al.*, Exploring the possibility space: Taking stock of the diverse capabilities and gaps in integrated assessment models. *Environ. Res. Lett.* **16**, 053006 (2021).
38. M. Harmsen *et al.*, Integrated assessment model diagnostics: key indicators and model evolution. *Environ. Res. Lett.* **16**, 054046 (2021).
39. L. van Beek *et al.*, Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970. *Global Environ. Change* **65**, 102191 (2020).
40. F. van Tongeren, H. van Meijl, Y. Surry, Global models applied to agricultural and trade policies: a review and assessment. *Agr. Econ.* **26**, 149-172 (2001).
41. B. L. Bodirsky *et al.*, Global Food Demand Scenarios for the 21st Century. *PLoS One* **10**, e0139201 (2015).
42. A. Muller *et al.*, Strategies for feeding the world more sustainably with organic agriculture. *Nat. Commun.* **8**, 1290 (2017).
43. K.-H. Erb *et al.*, Exploring the biophysical option space for feeding the world without deforestation. *Nat. Commun.* **7**, 11382 (2016).
44. Y. Li *et al.*, Changes in global food consumption increase GHG emissions despite efficiency gains along global supply chains. *Nat. Food.* **4**, 483-495 (2023).
45. A. D. Bayer, S. Lautenbach, A. Arneth, Benefits and trade-offs of optimizing global land use for food, water, and carbon. *PNAS* **120**, e2220371120 (2023).
46. A. C. Castonguay *et al.*, Navigating sustainability trade-offs in global beef production. *Nat. Sustain.*, (2023).
47. G. Martini *et al.*, Machine learning can guide food security efforts when primary data are not available. *Nat. Food.* **3**, 716-728 (2022).
48. D. S. Utomo, B. S. Onggo, S. Eldridge, Applications of agent-based modelling and simulation in the agri-food supply chains. *European Journal of Operational Research* **269**, 794-805 (2018).
49. M. van Dijk, T. Morley, M. L. Rau, Y. Saghai, A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nat. Food.* **2**, 494-501 (2021).
50. OECD, FAO, "Aglink-Cosimo Model - A partial equilibrium model of world agricultural markets," (OECD and FAO, Paris and Rome, 2022). Retrieved from: https://openknowledge.fao.org/handle/20.500.14283/cc1839en
51. W. Britz, P. Witzke, "CAPRI model documentation 2014," (2014). Retrieved from: http://www.capri-model.org/docs/capri_documentation.pdf
52. IBF-IIASA, "Global Biosphere Management Model (GLOBIOM) Documentation 2023 - Versi on 1.0," (Integrated Biospheres Futures, International Institute for Applied Sys tems Analysis (IBF-IIASA), Laxenburg, Austria, 2023). Retrieved from: https://pure.iiasa.ac.at/18996
53. S. Robinson *et al.*, "The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model documentation for version 3.6. Modeling Systems Technical Paper 1.," (International Food Policy Research Institut, Washington, DC, 2024). Retrieved from:
54. J. P. Dietrich *et al.*, MAgPIE 4 – a modular open-source framework for modeling global land systems. *Geosci. Model Dev.* **12**, 1299-1317 (2019).
55. U. L. C. Baldos, T. W. Hertel, Looking back to move forward on model validation: insights from a global model of agricultural land use. *Environ. Res. Lett.* **8**, 034024 (2013).
56. M. Cantele *et al.*, Equilibrium Modeling for Environmental Science: Exploring the Nexus of Economic Systems and Environmental Change. *Earth's Future* **9**, e2020EF001923 (2021).
57. T. Hasegawa *et al.*, Climate Change Impact and Adaptation Assessment on Food Consumption Utilizing a New Scenario Framework. *Environ. Sci. Technol.* **48**, 438-445 (2014).

58. W. Britz, D. van der Mensbrugghe, CGEBox: A Flexible, Modular and Extendable Framework for CGE Analysis in GAMS. *Journal of Global Economic Analysis* **3**, 106-177 (2018).
59. A. Calzadilla, R. Delzeit, G. Klepper, "DART-BIO: Modelling the interplay of food, feed and fuels in a global CGE model," (Kiel Institute for the World Economy, Kiel, Germany, 2014). Retrieved from: https://hdl.handle.net/10419/90629
60. T. Hertel, *Global Trade Analysis: Modeling and applications*. (Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, 1997).
61. L. L. Porfirio, D. Newth, J. J. Finnigan, Y. Cai, Economic shifts in agricultural production and trade due to climate change. *Palgrave Commun.* **4**, 111 (2018).
62. H. van Meijl, T. van Rheenen, A. Tabeau, B. Eickhout, The impact of different policy environments on agricultural land use in Europe. *Agriculture, Ecosystems & Environment* **114**, 21-38 (2006).
63. D. Laborde, A. Herforth, D. Headey, S. de Pee, COVID-19 pandemic leads to greater depth of unaffordability of healthy and nutrient-adequate diets in low- and middle-income countries. *Nat. Food.* **2**, 473-475 (2021).
64. K. Calvin *et al.*, GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. *Geosci. Model Dev.* **12**, 677-698 (2019).
65. E. Stehfest *et al.*, "Integrated Assessment of Global Environmental Change with IMAGE 3.0," (PBL Netherlands Environmental Assessment Agency, The Hague, 2014). Retrieved from: https://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-image-30-model-description-and-policy-applications
66. D. Willenbockel *et al.*, "Dynamic Computable General Equilibrium Simulations in Support of Quantitative Foresight Modeling to Inform the CGIAR Research Portfolio: Linking the IMPACT and GLOBE Models. IFPRI Discussion Paper.," (International Food Policy Research Institute, Washington DC, 2018). Retrieved from: https://ebrary.ifpri.org/digital/collection/p15738coll2/id/132757
67. S. S. Rabin *et al.*, Impacts of future agricultural change on ecosystem service indicators. *Earth Syst. Dynam.* **11**, 357-376 (2020).
68. H. van Meijl *et al.*, How food secure are the green, rocky and middle roads: food security effects in different world development paths. *Environmental Research Communications* **2**, 031002 (2020).
69. O. Fricko *et al.*, The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environ. Change* **42**, 251-267 (2017).
70. F. Humpenöder *et al.*, Food matters: Dietary shifts increase the feasibility of 1.5°C pathways in line with the Paris Agreement. *Sci. Adv.* **10**, eadj3832 (2024).
71. B. L. Bodirsky *et al.*, Integrating degrowth and efficiency perspectives enables an emission-neutral food system by 2100. *Nat. Food.* **3**, 341-348 (2022).
72. C. Conti, G. Zanello, A. Hall, Why are agri-food systems resistant to new directions of change? A systematic review. *Glob. Food Secur.* **31**, 100576 (2021).
73. M. Herrero *et al.*, Innovation can accelerate the transition towards a sustainable food system. *Nat. Food.* **1**, 266-272 (2020).
74. P. Forster *et al.*, "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development Supplementary Material," *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (2018). Retrieved from: https://www.ipcc.ch/sr15
75. C. Guivarch *et al.*, "Annex III: Scenarios and modelling methods," *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022). Retrieved from:
76. , (!!! INVALID CITATION !!! (Gerten et al., 2020; Van Vuuren et al., 2019)).
77. E. Rogers. (Free Press, New York, USA, 1962).
78. W. Britz, Estimating a global MAIDADS demand system considering demography, climate and norms. *Bio-based and Applied Economics* **3**, 219-238 (2021).
79. M. Avetisyan, U. Baldos, T. Hertel, "Development of the GTAP Version 7 Land Use Data Base," (Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, 2010). Retrieved from: https://EconPapers.repec.org/RePEc:gta:resmem:3426
80. M. Chepeliev, Incorporating Nutritional Accounts to the GTAP Data Base. *Journal of Global Economic Analysis* **7**, 1-43 (2022).
81. I. Haqiqi, F. Taheripour, J. Liu, D. van der Mensbrugghe, Introducing Irrigation Water into GTAP Data Base Version 9. *Journal of Global Economic Analysis* **1**, 116-155 (2016).
82. M. Chepeliev *et al.*, Disaggregating the Vegetables, Fruits and Nuts Sector to the Tariff Line in the GTAP-HS Framework. *Journal of Global Economic Analysis* **6**, 82-127 (2021).
83. W. Britz, Disaggregating Agro-Food Sectors in the GTAP Data Base. *Journal of Global Economic Analysis* **7**, 44-75 (2022).

84. T. Hasegawa *et al.*, Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Change.* **8**, 699-703 (2018).
85. A. Gatto, M. Kuiper, H. van Meijl, Economic, social and environmental spillovers decrease the benefits of a global dietary shift. *Nat. Food.* **4**, 496-507 (2023).
86. N. E. Jensen, An Introduction to Bernoullian Utility Theory: I. Utility Functions. *The Swedish Journal of Economics* **69**, 163-183 (1967).
87. F. Creutzig *et al.*, Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nat. Clim. Change.* **12**, 36-46 (2022).
88. M. Kuhn, S. Eker, C. Reiter, Q. Liu, in *Systems Analysis for Sustainable Wellbeing. 50 years of IIASA research, 40 years after the Brundtland Commission, contributing to the post-2030 Global Agenda,* W. Lutz, S. Pachauri, Eds. (IIASA, Laxenburg, Austria, 2023), pp. 61-76.
89. A. Wood *et al.*, Reframing the local–global food systems debate through a resilience lens. *Nat. Food.* **4**, 22-29 (2023).
90. A. Marrero *et al.*, Equity as a priority in EAT–Lancet-aligned food system transformations. *Nat. Food.* **5**, 811-817 (2024).
91. M. Obersteiner *et al.*, Assessing the land resource–food price nexus of the Sustainable Development Goals. *Sci. Adv.* **2**, e1501499 (2016).
92. H. Gosnell, N. Gill, M. Voyer, Transformational adaptation on the farm: Processes of change and persistence in transitions to 'climate-smart' regenerative agriculture. *Global Environ. Change* **59**, 101965 (2019).
93. M. Springmann *et al.*, Options for keeping the food system within environmental limits. *Nature* **562**, 519-525 (2018).
94. E. Stehfest *et al.*, Climate benefits of changing diet. *Clim. Change* **95**, 83-102 (2009).
95. M. A. Clark *et al.*, Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science* **370**, 705-708 (2020).
96. F. Creutzig *et al.*, in *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2022), pp. 752-943.
97. K. Nyborg *et al.*, Social norms as solutions. *Science* **354**, 42-43 (2016).
98. D. Sarkar, J. Walker-Swaney, K. Shetty, Food Diversity and Indigenous Food Systems to Combat Diet-Linked Chronic Diseases. *Current Developments in Nutrition* **4**, 3-11 (2020).
99. E. Brutschin *et al.*, A multidimensional feasibility evaluation of low-carbon scenarios. *Environ. Res. Lett.* **16**, 064069 (2021).
100. J. Jewell, A. Cherp, The feasibility of climate action: Bridging the inside and the outside view through feasibility spaces. *WIREs Climate Change* **n/a**, e838 (2023).
101. T. A. Domencich, D. McFadden, *Urban Travel Demand—A Behavioural Analysis*. (North-Holland Publishing, 1975).
102. A. Tversky, D. J. s. Kahneman, Judgment under uncertainty: Heuristics and biases. *Science* **185**, 1124-1131 (1974).
103. R. Thaler, C. Sunstein, *Nudge: Improving decisions about health, wealth and happiness*. (Yale University Press, New Haven, 2008).
104. T. M. Lenton *et al.*, Operationalising positive tipping points towards global sustainability. *Glob. Sustain.* **5**, e1 (2022).
105. D. Centola, J. Becker, D. Brackbill, A. Baronchelli, Experimental evidence for tipping points in social convention. *Science* **360**, 1116-1119 (2018).
106. U. Sanga, J. Berrío-Martínez, M. Schlüter, Modelling agricultural innovations as a social-ecological phenomenon. *Socio-Environmental Systems Modelling* **5**, 18562 (2023).
107. S. Eker, G. Reese, M. Obersteiner, Modelling the drivers of a widespread shift to sustainable diets. *Nat. Sustain.* **2**, 725–735 (2019).
108. D. Wuepper *et al.*, Public policies and global forest conservation: Empirical evidence from national borders. *Global Environ. Change* **84**, 102770 (2024).
109. P. Matous, Ö. Bodin, Hub-and-spoke social networks among Indonesian cocoa farmers homogenise farming practices. *People and Nature* **6**, 598-609 (2024).
110. N. Davis, B. Dermody, M. Koetse, G. van Voorn, Identifying Personal and Social Drivers of Dietary Patterns: An Agent-Based Model of Dutch Consumer Behavior. *Journal of Artificial Societies and Social Simulation* **27**, 4 (2024).
111. B. A. Langellier *et al.*, Potential impacts of policies to reduce purchasing of ultra-processed foods in Mexico at different stages of the social transition: an agent-based modelling approach. *Public Health Nutr.* **25**, 1711-1719 (2022).
112. N. J. Turner, A. Cuerrier, L. Joseph, Well grounded: Indigenous Peoples' knowledge, ethnobiology and sustainability. *People and Nature* **4**, 627-651 (2022).
113. J. Köhler *et al.*, An agenda for sustainability transitions research: State of the art and future directions. *Environ. Innov. Soc. Transit.* **31**, 1-32 (2019).

114. H. H. E. van Zanten *et al.*, Circularity in Europe strengthens the sustainability of the global food system. *Nat. Food.* **4**, 320-330 (2023).
115. K. Brown, J. Schirmer, P. Upton, Can regenerative agriculture support successful adaptation to climate change and improved landscape health through building farmer self-efficacy and wellbeing? *Current Research in Environmental Sustainability* **4**, 100170 (2022).
116. F. Rydzak *et al.*, "FeliX3 – Impact Assessment Model Systemic view across Societal Benefit Areas beyond Global Earth Observation (Model Report and Technical Documentation)," (International Institute for Applied Systems Analysis (IIASA), Laxenburg, 2013). Retrieved from: https://bit.ly/3OcXwLQ
117. S. Eker, Q. Liu, C. Reiter, M. Kuhn, "Full of Economic-Environment Linkages and Integration dX/dt (FeliX): Technical Model Documentation (No. ZVR 524808900)," (International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 2023). Retrieved from: https://iiasa.ac.at/models-tools-data/felix
118. F. Rydzak, M. Obersteiner, F. Kraxner, Impact of global Earth observation systemic view across GEOSS societal benefit area. *Int. J. Spat. Data Infrastruct. Res.*, 216–243 (2010).
119. B. Walsh *et al.*, Pathways for balancing CO2 emissions and sinks. *Nat. Commun.* **8**, 14856 (2017).
120. E. A. Moallemi *et al.*, Early systems change necessary for catalyzing long-term sustainability in a post-2030 agenda. *One Earth* **5**, 1–20 (2022).
121. Q. Liu *et al.*, Robust strategies to end global poverty and reduce environmental pressures. *One Earth* **6**, 1–17 (2023).
122. L. Pereira *et al.*, Transformative spaces in the making: key lessons from nine cases in the Global South. *Sustain. Sci.* **15**, 161-178 (2020).
123. A. Leip *et al.*, Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen and carbon losses from arable soils in Europe. *Biogeosciences* **5**, 73-94 (2008).
124. W. Britz, P. H. Verburg, A. Leip, Modelling of land cover and agricultural change in Europe: Combining t he CLUE and CAPRI-Spat approaches. *Scaling methods in integrated assessment of agricultural systems* **142**, 40-50 (2011).
125. A. Gocht, W. Britz, EU-wide farm type supply models in CAPRI—How to consistently disaggregate sector models into farm type models. *J. Pol. Modeling* **33**, 146-167 (2011).
126. K. Mittenzwei, W. Britz, Analysing Farm-specific Payments for Norway using the Agrispace Model. *J. Agr. Econ.* **69**, 777-793 (2018).
127. K. Mittenzwei, W. Britz, R. J. F. Burton, The potential impact of cultivated protein on agriculture in Norway. *Environ. Innov. Soc. Transit.* **55**, 100960 (2025).
128. W. Britz, M. K. van Ittersum, A. G. J. M. Oude Lansink, T. Heckelei, Tools for Integrated Assessment in Agriculture. State of the Art and Challenges. *Bio-based and Applied Economics Journal*. 2012 (ISSN 2280-6172

10.22004/ag.econ.141966

Other

doi).
129. L. Shang *et al.*, Surrogate modelling of a detailed farm-level model using deep learning. *J. Agr. Econ.* **75**, 235-260 (2024).
130. L. Shang *et al.*, Adoption and diffusion of digital farming technologies - integrating farm-level evidence and system interaction. *Agric. Syst.* **190**, 103074 (2021).
131. J. A. Johnson *et al.*, Investing in nature can improve equity and economic returns. *PNAS* **120**, e2220401120 (2023).
132. A. Mosnier *et al.*, How can diverse national food and land-use priorities be reconciled with global sustainability targets? Lessons from the FABLE initiative. *Sustain. Sci.* **18**, 335-345 (2023).
133. H. Zhao *et al.*, China's future food demand and its implications for trade and environment. *Nat. Sustain.* **4**, 1042-1051 (2021).
134. A. C. Soterroni *et al.*, Future environmental and agricultural impacts of Brazil's Forest Code. *Environ. Res. Lett.* **13**, 074021 (2018).
135. X. Wang *et al.*, Reforming China's fertilizer policies: implications for nitrogen pollution reduction and food security. *Sustain. Sci.* **18**, 407-420 (2023).
136. M. Binsted *et al.*, GCAM-USA v5.3_water_dispatch: integrated modeling of subnational US energy, water, and land systems within a global framework. *Geosci. Model Dev.* **15**, 2533-2559 (2022).
137. B. Kopainsky, G. Hager, H. Herrera, P. H. Nyanga, Transforming food systems at local levels: Using participatory system dynamics in an interactive manner to refine small-scale farmers' mental models. *Ecological Modelling* **362**, 101-110 (2017).
138. C. Wentworth *et al.*, Navigating community engagement in participatory modeling of food systems. *Environ. Sci. Policy* **152**, 103645 (2024).

139. J. T. M. Davis, P. H. Verburg, J. D. May, Diverse actor perspectives on African urban food systems: lessons from participatory food system modeling in Worcester, South Africa. *Ecol. Soc.* **28**, (2023).
140. A. Inam *et al.*, Coupling of a distributed stakeholder-built system dynamics socio-economic model with SAHYSMOD for sustainable soil salinity management. Part 2: Model coupling and application. *J. Hydrol* **551**, 278-299 (2017).
141. A. C. Mangnus *et al.*, New pathways for governing food system transformations: a pluralistic practice-based futures approach using visioning, back-casting, and serious gaming. *Ecol. Soc.* **24**, (2019).
142. K. Muiderman *et al.*, The anticipatory governance of sustainability transformations: Hybrid approaches and dominant perspectives. *Global Environ. Change* **73**, 102452 (2022).
143. A. Hebinck *et al.*, Imagining transformative futures participatory foresight for food systems change. *Ecol. Soc.* **23**, (2018).
144. N. Iñiguez, "Leveraging Indigenous Knowledge and Modern Science for Sustainable Food System Transformation," (Rockefeller Foundation, USA, 2024). Retrieved from: https://coilink.org/20.500.12592/r2285rv
145. R. Bandari *et al.*, Prioritising Sustainable Development Goals, characterising interactions, and identifying solutions for local sustainability. *Environ. Sci. Policy* **127**, 325-336 (2021).
146. R. Bandari *et al.*, Transdisciplinary approaches to local sustainability: aligning local governance and navigating spillovers with global action towards the Sustainable Development Goals. *Sustain. Sci.*, (2024).
147. S. Bankes, Exploratory modeling for policy analysis. *Oper. Res.* **41**, 435-449 (1993).
148. L. M. Aston, J. N. Smith, J. W. Powles, Impact of a reduced red and processed meat dietary pattern on disease risks and greenhouse gas emissions in the UK: a modelling study. *BMJ Open* **2**, e001072 (2012).
149. V. Srikrishnan *et al.*, Uncertainty Analysis in Multi-Sector Systems: Considerations for Risk Analysis, Projection, and Planning for Complex Systems. *Earth's Future* **10**, e2021EF002644 (2022).
150. J. C. Doelman *et al.*, Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. *Global Environ. Change* **48**, 119-135 (2018).
151. H. Valin *et al.*, "Achieving Zero Hunger by 2030 A Review of Quantitative Assessments of Synergies and Tradeoffs amongst the UN Sustainable Development Goals," (Bonn: Center for Development Research (ZEF) in cooperation with the Scientific Group for the UN Food System Summit 2021, 2021). Retrieved from:
152. C. Schmitz *et al.*, Land-use change trajectories up to 2050: insights from a global agro-economic model comparison. *Agr. Econ.* **45**, 69-84 (2013).
153. R. Prestele *et al.*, Hotspots of uncertainty in land-use and land-cover change projections: a global-scale model comparison. *Global Change Biology* **22**, 3967-3983 (2016).
154. A. Stirling, Keep it complex. *Nature* **468**, 1029-1031 (2010).
155. C. Guivarch *et al.*, Using large ensembles of climate change mitigation scenarios for robust insights. *Nat. Clim. Change.* **12**, 428-435 (2022).
156. M. Hadjikakou *et al.*, Ambitious food system interventions required to mitigatethe risk of exceeding Earth's environmental limits. *EarthArXiv preprint*, (2024).
157. C. Rosenzweig *et al.*, The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agricultural and Forest Meteorology* **170**, 166-182 (2013).
158. I. Pérez-Domínguez *et al.*, Short- and long-term warming effects of methane may affect the cost-effectiveness of mitigation policies and benefits of low-meat diets. *Nat. Food.* **2**, 970-980 (2021).
159. S. Fujimori *et al.*, Land-based climate change mitigation measures can affect agricultural markets and food security. *Nat. Food.* **3**, 110-121 (2022).
160. S. Razavi, B. A. Tolson, D. H. Burn, Review of surrogate modeling in water resources. *Water Resources Res.* **48**, (2012).
161. M. S. Khan *et al.*, Quantifying the Safe Operating Space for Land-System SDG Achievement via Machine Learning and Scenario Discovery. *Earth's Future* **11**, e2022EF003083 (2023).
162. G. Zhao *et al.*, Large-scale, high-resolution agricultural systems modeling using a hybrid approach combining grid computing and parallel processing. *Environ. Model. Software* **41**, 231-238 (2013).
163. D. Harrison-Atlas, R. N. King, A. Glaws, Machine learning enables national assessment of wind plant controls with implications for land use. *Wind Energy* **25**, 618-638 (2022).
164. G. C. Nelson *et al.*, Agriculture and climate change in global scenarios: why don't the models agree. *Agr. Econ.* **45**, 85-101 (2014).
165. D. Spiegelhalter, M. Pearson, I. Short, Visualizing Uncertainty About the Future. *Science* **333**, 1393-1400 (2011).
166. N. N. Taleb, *The black swan: the impact of the highly improbable*. (Random House, New York, 2007).
167. M. Haasnoot, J. H. Kwakkel, W. E. Walker, J. ter Maat, Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environ. Change* **23**, 485-498 (2013).

168. K. Mausch *et al.*, Embracing uncertainty: Foundations of a learning system for food systems transformation. *EarthArXive (pre-print)*, (2024).
169. I. Scoones, *Navigating Uncertainty: Radical Rethinking for a Turbulent World*. (Polity Press, UK, 2024).
170. J. Rockström *et al.*, Safe and just Earth system boundaries. *Nature*, (2023).
171. M. D. Mastrandrea, S. H. Schneider, Probabilistic Integrated Assessment of "Dangerous" Climate Change. *Science* **304**, 571-575 (2004).
172. M. Gibson *et al.*, Degrowth as a plausible pathway for food systems transformation. *Nat. Food.*, (2025).
173. M. Herrero *et al.*, Articulating the effect of food systems innovation on the Sustainable Development Goals. *The Lancet Planetary Health* **5**, e50-e62 (2021).
174. C. Zimm, T. Schinko, S. Pachauri, Putting multidimensional inequalities in human wellbeing at the centre of transitions. *The Lancet Planetary Health* **6**, e641-e642 (2022).
175. S. Whitten *et al.*, "Exploring Climate Risk in Australia: The economic implications of a delayed transition to net zero emissions," (CSIRO, Australia, 2021). Retrieved from: https://ecos.csiro.au/wp-content/uploads/2022/02/Technical-Report__Exploring-Climate-Risk-in-Australia__20220204.pdf
176. CWC, "Land use futures – natural capital roadmap," (ClimateWorks Centre, Australia, 2019). Retrieved from: https://www.climateworksaustralia.org/resource/land-use-futures-natural-capital-roadmap/
177. M. Miller, *Designing Regenerative Transitions*. University of Technology Sydney, Australia (2024).
178. J. S. Collie *et al.*, Ecosystem models for fisheries management: finding the sweet spot. *Fish Fish.* **17**, 101-125 (2016).
179. É. E. Plagányi *et al.*, Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity. *Fish Fish.* **15**, 1-22 (2014).
180. M. van Dijk, T. Morley, M. Luise Rau, Y. Saghai. (2021).
181. A. C. Castonguay *et al.* (2023).
182. S. K. Jones, A. Monjeau, K. Perez-Guzman, P. A. Harrison, Integrated modeling to achieve global goals: lessons from the Food, Agriculture, Biodiversity, Land-use, and Energy (FABLE) initiative. *Sustain. Sci.* **18**, 323-333 (2023).
183. K. C. Green, J. S. Armstrong, Simple versus complex forecasting: The evidence. *J. Bus. Res.* **68**, 1678-1685 (2015).
184. A. Gambhir, G. Ganguly, S. Mittal, Climate change mitigation scenario databases should incorporate more non-IAM pathways. *Joule*, (2022).
185. K. Koasidis, A. Nikas, H. Doukas, Why integrated assessment models alone are insufficient to navigate us through the polycrisis. *One Earth* **6**, 205-209 (2023).
186. N. Collins *et al.*, Design and Implementation of Components in the Earth System Modeling Framework. *The International Journal of High Performance Computing Applications* **19**, 341-350 (2005).
187. S. Friedenthal, A. Moore, R. Steiner, *A practical guide to SysML: the systems modeling language*. (Morgan Kaufmann, 2014).
188. J. S. Morgan, S. Howick, V. Belton, A toolkit of designs for mixing Discrete Event Simulation and System Dynamics. *European Journal of Operational Research* **257**, 907-918 (2017).
189. J. C. Doelman, E. Stehfest, A. Tabeau, H. van Meijl, Making the Paris agreement climate targets consistent with food security objectives. *Glob. Food Secur.* **23**, 93-103 (2019).
190. M. S. Khan *et al.*, Machine learning-based surrogate modelling of a robust, sustainable development goal (SDG)-compliant land-use future for Australia at high spatial resolution. *J. Environ. Manage.* **363**, 121296 (2024).
191. E. A. Moallemi *et al.*, Structuring and evaluating decision support processes to enhance the robustness of complex human–natural systems. *Environ. Model. Software* **123**, 1045-1051 (2020).
192. A. Saltelli *et al.*, Bring digital twins back to Earth. *WIREs Climate Change* **n/a**, e915 (2024).
193. A. Puy *et al.*, Models with higher effective dimensions tend to produce more uncertain estimates. *Sci. Adv.* **8**, eabn9450 (2022).
194. M. Bunge, *Emergence and Convergence: Qualitative Novelty and the Unity of Knowledge*. Toronto studies in philosophy (University of Toronto Press Incorporated, Toronto, 2003).
195. D. H. Meadows, *Thinking in systems: A primer*. D. Wright, Ed., (Chelsea Green Publishing, Vermont, USA, 2008).
196. I. Stewart, *Does God Play Dice: The New Mathematics of Chaos*. (Blackwell Publishing, Hoboken, New Jersey, USA, 1989).
197. A. Saltelli, M. Giampietro, What is wrong with evidence based policy, and how can it be improved? *Futures* **91**, 62-71 (2017).
198. C. Conti *et al.*, A quest for questions: a tool for navigating just food system transformations in an era of uncertainty. *SSRN (preprint)*, (2024).
199. S. Razavi *et al.*, The Future of Sensitivity Analysis: An essential discipline for systems modeling and policy support. *Environ. Model. Software* **137**, 104954 (2021).

200. A. Saltelli *et al.*, Five ways to ensure that models serve society: a manifesto. *Nature*, 482–484 (2020).
201. D. Leclère *et al.*, Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551–556 (2020).
202. H. Zhao *et al.*, Holistic food system innovation strategies can close up to 80% of China's domestic protein gaps while reducing global environmental impacts. *Nat. Food.* **5**, 581-591 (2024).
203. Z. Doğan, S. Arslan, A. G. Köksal, Historical development of agricultural accounting and difficulties encountered in the implementation of agricultural accounting. *International Journal of Food and Agricultural Economics (IJFAEC)*. 2013 (10.22004/ag.econ.160099

doi).
204. M. W. Rosegrant, N. Leach, R. V. Gerpacio, Alternative futures for world cereal and meat consumption. *Proc. Nutr. Soc.* **58**, 219-234 (1999).
205. D. Mason-D'Croz *et al.*, Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. *Lancet Planet Health* **3**, e318-e329 (2019).
206. M. Springmann *et al.*, Global and regional health effects of future food production under climate change: a modelling study. *The Lancet* **387**, 1937-1946 (2016).
207. P. Havlík *et al.*, Global land-use implications of first and second generation biofuel targets. *Energy Policy* **39**, 5690-5702 (2011).
208. P. Havlík *et al.*, Climate change mitigation through livestock system transitions. *PNAS* **111**, 3709-3714 (2014).
209. U. L. C. Baldos *et al.*, SIMPLE-G: A multiscale framework for integration of economic and biophysical determinants of sustainability. *Environ. Model. Software* **133**, 104805 (2020).
210. S. Fujimori, T. Masui, Y. Matsuoka, AIM/CGE [basic] manual *Discussion Paper Series: Center for Social and Environmental Systems Research, NIES*, (2012).
211. A. Calzadilla, K. Rehdanz, R. S. J. Tol, The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis. *J. Hydrol* **384**, 292-305 (2010).
212. N. B. Villoria, A. Golub, D. Byerlee, J. Stevenson, Will Yield Improvements on the Forest Frontier Reduce Greenhouse Gas Emissions? A Global Analysis of Oil Palm. *American Journal of Agricultural Economics* **95**, 1301-1308 (2013).
213. F. Taheripour *et al.*, Biofuels and their by-products: Global economic and environmental implications. *Biomass Bioenergy* **34**, 278-289 (2010).
214. W. Britz, R. Roson, G-RDEM: A GTAP-Based Recursive Dynamic CGE Model for Long-Term Baselin e Generation and Analysis. *Journal of Global Economic Analysis* **4**, 50-96 (2019).
215. F. C. Moore, U. L. C. Baldos, T. Hertel, Economic impacts of climate change on agriculture: a comparison of process-based and statistical yield models. *Environ. Res. Lett.* **12**, 065008 (2017).
216. H. Pant, "GTEM: Global trade and environment model. ABARE technical report.," (Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, 2007). Retrieved from:
217. A. Bouët *et al.*, "MIRAGRODEP 2.0: Documentation. AGRODEP Technical Note TN-26," (International Food Policy Research Institute (IFPRI), Washington, DC, 2022). Retrieved from:
218. M. Awais *et al.*, MESSAGEix-GLOBIOM nexus module: integrating water sector and climate impacts. *Geosci. Model Dev.* **17**, 2447-2469 (2024).
219. K. Riahi *et al.*, Cost and attainability of meeting stringent climate targets without overshoot. *Nat. Clim. Change.* **11**, 1063-1069 (2021).
220. V. Krey *et al.*, "MESSAGE-GLOBIOM 1.0 Documentation," (IIASA, Austria, 2016). Retrieved from:
221. N. Bauer *et al.*, Bio-energy and CO2 emission reductions: an integrated land-use and energy sector perspective. *Clim. Change* **163**, 1675-1693 (2020).
222. P. Alexander *et al.*, Adaptation of global land use and management intensity to changes in climate and atmospheric carbon dioxide. *Global Change Biology* **24**, 2791-2809 (2018).
223. A. Molotoks *et al.*, Comparing the impact of future cropland expansion on global biodiversity and carbon storage across models and scenarios. *Philosophical Transactions of the Royal Society B: Biological Sciences* **375**, 20190189 (2020).
224. D. Mason-D'Croz *et al.*, Modelling the global economic consequences of a major African swine fe ver outbreak in China. *Nat. Food.* **1**, 221-228 (2020).
225. D. Mason-D'Croz *et al.*, Agricultural investments and hunger in Africa modeling potential contr ibutions to SDG2 – Zero Hunger. *World Devel.* **116**, 38-53 (2019).
226. S. McDonald, S. Robinson, K. Thierfelder, "GLOBE: A SAM Based Global CGE Model Using GTAP Data Departmental Working Papers 14," (United States Naval Academy Department of Economics, 2007). Retrieved from:
227. A. Kavallari, P. Conforti, D. van der Mensbrugghe, "The Global Agriculture Perspectives System (GAPS): Version 1.0. ESA Working Paper No. 16," (FAO, Rome, Italy, 2016). Retrieved from:

228. D. Van der Mensbrugghe, "The environmental impact and sustainability applied general equilibrium (ENVISAGE) model version 10.1. GTP/19/01 GTAP Technical Paper," (Center for Global Trade Analysis Purdue University West Lafayette, 2018). Retrieved from:
229. S. Paltsev *et al.*, "The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. Joint Program Report Series Report.," (2005). Retrieved from: http://globalchange.mit.edu/publication/14578
230. Y.-H. H. Chen *et al.*, "The MIT Economic Projection and Policy Analysis (EPPA) Model: Version 5. Joint Program Technical Note TN #16," (2017). Retrieved from: http://globalchange.mit.edu/publication/16620
231. R. D. Sands, H. Förster, C. A. Jones, K. Schumacher, Bio-electricity and land use in the Future Agricultural Resources Model (FARM). *Clim. Change* **123**, 719-730 (2014).
232. M. Li *et al.*, Global food-miles account for nearly 20% of total food-systems emissions. *Nat. Food.* **3**, 445-453 (2022).
233. M. Bruckner *et al.*, FABIO—The Construction of the Food and Agriculture Biomass Input–Output Model. *Environ. Sci. Technol.* **53**, 11302-11312 (2019).
234. S. Hallegatte, An Adaptive Regional Input-Output Model and its Application to the Assessment of the Economic Cost of Katrina. *Risk Anal.* **28**, 779-799 (2008).
235. H. Zhang *et al.*, Global environmental impacts of food system from regional shock: Russia-Ukraine war as an example. *Humanities and Social Sciences Communications* **11**, 191 (2024).
236. A. Uwizeye *et al.*, Nitrogen emissions along global livestock supply chains. *Nat. Food.* **1**, 437-446 (2020).
237. M. J. MacLeod *et al.*, Invited review: A position on the Global Livestock Environmental Assessment Model (GLEAM). *Animal* **12**, 383-397 (2018).
238. J. G. Conijn, P. S. Bindraban, J. J. Schröder, R. E. E. Jongschaap, Can our global food system meet food demand within planetary boundaries? *Agriculture, Ecosystems & Environment* **251**, 244-256 (2018).
239. M. C. Theurl *et al.*, Food systems in a zero-deforestation world: Dietary change is more important than intensification for climate targets in 2050. *Sci. Total Environ.* **735**, 139353 (2020).
240. T. G. Morais *et al.*, Agroecological measures and circular economy strategies to ensure sufficient nitrogen for sustainable farming. *Global Environ. Change* **69**, 102313 (2021).
241. G. Kalt *et al.*, Exploring the option space for land system futures at regional to global scales: The diagnostic agro-food, land use and greenhouse gas emission model BioBaM-GHG 2.0. *Ecological Modelling* **459**, 109729 (2021).
242. C. Schader *et al.*, Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. *Journal of The Royal Society Interface* **12**, 20150891 (2015).
243. T. W. R. Powell, T. M. Lenton, Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. *Energy Environ. Sci.* **5**, 8116-8133 (2012).
244. T. S. Ball *et al.*, C-LLAMA 1.0: a traceable model for food, agriculture, and land use. *Geosci. Model Dev.* **15**, 929-949 (2022).
245. Q. Ye *et al.*, FeliX 2.0: An integrated model of climate, economy, environment, and society interactions. *Environ. Model. Software* **179**, 106121 (2024).
246. E. Lucas, M. Guo, G. Guillén-Gosálbez, Low-carbon diets can reduce global ecological and health costs. *Nat. Food.* **4**, 394-406 (2023).
247. D. Tilman, M. Clark, Global diets link environmental sustainability and human health. *Nature* **515**, 518-522 (2014).
248. X. Chen *et al.*, Physical and virtual nutrient flows in global telecoupled agricultural trade networks. *Nat. Commun.* **14**, 2391 (2023).
249. Y. Li *et al.*, Reducing climate change impacts from the global food system through diet shifts. *Nat. Clim. Change.* **14**, 943-953 (2024).
250. S. Corrado *et al.*, Unveiling the potential for an efficient use of nitrogen along the food supply and consumption chain. *Glob. Food Secur.* **25**, 100368 (2020).
251. L. Xue *et al.*, China's food loss and waste embodies increasing environmental impacts. *Nat. Food.* **2**, 519-528 (2021).
252. H. van Meijl *et al.*, Comparing impacts of climate change and mitigation on global agriculture by 2050. *Environ. Res. Lett.* **13**, 064021 (2018).
253. S. Fujimori *et al.*, A multi-model assessment of food security implications of climate change mitigation. *Nat. Sustain.* **2**, 386-396 (2019).
254. B. L. Bodirsky *et al.*, The ongoing nutrition transition thwarts long-term targets for food se curity, public health and environmental protection. *Sci. Rep.* **10**, 19778 (2020).
255. Y. Zeng, Y. Rao, Z. Xu, Anticipated cancer burden of low individual fruit and vegetable consum ption under climate change: A modelling study in China. *The International Journal of Health Planning and Management* **38**, 149-161 (2023).

256. R. C. Henry *et al.*, Global and regional health and food security under strict conservation scenarios. *Nat. Sustain.* **5**, 303-310 (2022).
257. J. Maire *et al.*, How different COVID-19 recovery paths affect human health, environmental sustainability, and food affordability: a modelling study. *Lancet Planet. Health* **6**, E565-E576 (2022).
258. H. Valin *et al.*, The future of food demand: understanding differences in global economi c models. *Agr. Econ.* **45**, 51-67 (2013).
259. G. Philippidis *et al.*, Eating your greens: a global sustainability assessment. *Resources, Conservation and Recycling* **168**, 105460 (2021).
260. Jgcri. (2023).
261. C. Ringler *et al.*, Global linkages among energy, food and water: an economic assessment. *Journal of Environmental Studies and Sciences* **6**, 161-171 (2016).
262. M. W. Rosegrant *et al.*, Food and nutrition security under changing climate and socioeconomic c onditions. *Glob. Food Secur.* **41**, 100755 (2024).
263. A. Kavallari, T. Fellmann, S. H. Gay, Shocks in economic growth shocking effects for food security? *Food Security* **6**, 567-583 (2014).
264. T. Hasegawa, S. Fujimori, K. Takahashi, T. Masui, Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. *Environ. Res. Lett.* **10**, 014010 (2015).
265. H. van Meijl *et al.*, Modelling alternative futures of global food security: Insights from FOODSECURE. *Glob. Food Secur.* **25**, 100358 (2020).
266. D. Laborde, W. Martin, R. Vos, Impacts of COVID-19 on global poverty, food security, and diets: Insig hts from global model scenario analysis. *Agr. Econ.* **52**, 375-390 (2021).
267. J. P. Dietrich, B. L. Bodirsky, I. Weindl, F. Humpenöder. (2024).
268. H. Bartelings, G. Philippidis, A novel macroeconomic modelling assessment of food loss and waste in t he EU: An application to the sustainable development goal of halving h ousehold food waste. *Sustainable Production and Consumption* **45**, 567-581 (2024).
269. C. Janssens *et al.*, Global hunger and climate change adaptation through international trad e. *Nat. Clim. Change.* **10**, 829-835 (2020).
270. C. Janssens *et al.*, A sustainable future for Africa through continental free trade and agr icultural development. *Nat. Food.* **3**, 608-618 (2022).
271. X. Zhao *et al.*, The impact of agricultural trade approaches on global economic modelin g. *Global Environ. Change* **73**, 102413 (2022).
272. D. Laborde Debucquet, W. Martin, Implications of the global growth slowdown for rural poverty. *Agr. Econ.* **49**, 325-338 (2018).
273. T. Hasegawa *et al.*, Global land-use allocation model linked to an integrated assessment mo del. *Sci. Total Environ.* **580**, 787-796 (2017).
274. N. Escobar, S. Haddad, J. Börner, W. Britz, Land use mediated GHG emissions and spillovers from increased consumption of bioplastics. *Environ. Res. Lett.* **13**, 125005 (2018).
275. X. Zhao, B. K. Mignone, M. A. Wise, H. C. McJeon, Trade-offs in land-based carbon removal measures under 1.5 °C and 2 °C futures. *Nat. Commun.* **15**, 2297 (2024).
276. M. J. Gidden *et al.*, Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. *Geosci. Model Dev.* **12**, 1443-1475 (2019).
277. H. Ohashi *et al.*, Biodiversity can benefit from climate stabilization despite adverse si de effects of land-based mitigation. *Nat. Commun.* **10**, 5240 (2019).
278. T. Goebel, W. Britz, A Computable General Equilibrium Modelling Approach to Assess Biodiversity Effects in Highly Detailed Global Long-Run Analysis. paper presented at the The 26th Annual Conference on Global Economic Analysis, Bordeaux, France, 2023.
279. A. Molotoks *et al.*, Global projections of future cropland expansion to 2050 and direct imp acts on biodiversity and carbon storage. *Global Change Biology* **24**, 5895-5908 (2018).
280. P. J. von Jeetze *et al.*, Projected landscape-scale repercussions of global action for climate and biodiversity protection. *Nat. Commun.* **14**, 2515 (2023).
281. V. Potopová *et al.*, Water Consumption by Livestock Systems from 2002–2020 and Predictions for 2030–2050 under Climate Changes in the Czech Republic. *Agriculture* **13**, 1291 (2023).
282. T. Kompas, T. N. Che, R. Q. Grafton, Global impacts of heat and water stress on food production and severe food insecurity. *Sci. Rep.* **14**, (2024).
283. D. P. van Vuuren *et al.*, Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environ. Change* **42**, 237-250 (2017).
284. H. Niazi *et al.*, Global peak water limit of future groundwater withdrawals. *Nat. Sustain.* **7**, 413-422 (2024).
285. J. Chang *et al.*, Reconciling regional nitrogen boundaries with global food security. *Nat. Food.* **2**, 700-711 (2021).
286. B. L. Bodirsky *et al.*, Current state and future scenarios of the global agricultural nitrogen cycle. *Biogeosci. Disc.* **9**, 2755 (2012).

287. A. F. Bouwman *et al.*, Global trends and uncertainties in terrestrial denitrification and N2O emissions. *Philosophical Transactions of the Royal Society B: Biological Sciences* **368**, 20130112 (2013).
288. L. Bouwman *et al.*, Exploring global changes in nitrogen and phosphorus cycles in agricult ure induced by livestock production over the 1900–2050 period. *PNAS* **110**, 20882-20887 (2011).
289. P. Kyle *et al.*, Assessing Multi-Dimensional Impacts of Achieving Sustainability Goals by Projecting the Sustainable Agriculture Matrix Into the Future. *Earth's Future* **11**, e2022EF003323 (2023).
290. A. H. W. Beusen *et al.*, Exploring river nitrogen and phosphorus loading and export to global coastal waters in the Shared Socio-economic pathways. *Global Environmental Change-Human and Policy Dimensions* **72**, (2022).
291. T. Fellmann *et al.*, Greenhouse gas mitigation technologies in agriculture: Regional circum stances and interactions determine cost-effectiveness. *Journal of Cleaner Production* **317**, 128406 (2021).
292. S. Frank *et al.*, Structural change as a key component for agricultural non-CO2 mitigati on efforts. *Nat. Commun.* **9**, 1060 (2018).
293. S. Frank *et al.*, Reducing greenhouse gas emissions in agriculture without compromising food security? *Environ. Res. Lett.* **12**, 105004 (2017).
294. F. Humpenöder *et al.*, Investigating afforestation and bioenergy CCS as climate change mitiga tion strategies. *Environ. Res. Lett.* **9**, 064029 (2014).
295. S. Frank *et al.*, Enhanced agricultural carbon sinks provide benefits for farmers and th e climate. *Nat. Food.* **5**, 742-753 (2024).
296. S. Islam *et al.*, Structural approaches to modeling the impact of climate change and ada ptation technologies on crop yields and food security. *Glob. Food Secur.* **10**, 63-70 (2016).
297. A. M. Thomson *et al.*, The contribution of future agricultural trends in the US Midwest to gl obal climate change mitigation. *Global Environ. Change* **24**, 143-154 (2014).
298. J. C. Doelman *et al.*, Afforestation for climate change mitigation: Potentials, risks and tra de-offs. *Global Change Biology* **26**, 1576-1591 (2020).
299. S. Roe *et al.*, Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Change.* **9**, 817-828 (2019).
300. S. Fujimori, T. Hasegawa, T. Masui, in *Post-2020 Climate Action: Global and Asian Perspectives,* S. Fujimori, M. Kainuma, T. Masui, Eds. (Springer Singapore, Singapore, 2017), pp. 305-328.
301. G. Philippidis *et al.*, Snakes and ladders: World development pathways' synergies and trade-of fs through the lens of the Sustainable Development Goals. *Journal of Cleaner Production* **267**, 122147 (2020).
302. P. Patel *et al.*, Core Model Proposal# 332: GCAM Macro-Economic Module (KLEM Version). *Joint Global Change Research Institute, Pacific Northwest National Lab oratory and the University of Maryland, College Park. PNNL-34479. http s://jgcri. github. io/gcam-doc/cmp/332-GCAM_Macro_Economic_Module_KLEM . pdf*, (2023).
303. M. Ho *et al.*, Modelling Consumption and Constructing Long-Term Baselines in Final Demand. *Journal of Global Economic Analysis* **5**, 63-108 (2020).
304. P. Alexander *et al.*, High energy and fertilizer prices are more damaging than food export c urtailment from Ukraine and Russia for food prices, health and the env ironment. *Nat. Food.* **4**, 84-95 (2023).
305. T. Jansson, S. Säll, Environmental Consumption Taxes on Animal Food Products to Mitigate Gr eenhouse Gas Emissions from the European Union. *Climate Change Economics* **9**, 1-16 (2018).
306. T. Fellmann, S. Hélaine, O. Nekhay, Harvest failures, temporary export restrictions and global food securi ty: the example of limited grain exports from Russia, Ukraine and Kaza khstan. *Food Security* **6**, 727-742 (2014).
307. S. R. Araujo Enciso, T. Fellmann, I. Pérez Dominguez, F. Santini, Abolishing biofuel policies: Possible impacts on agricultural price le vels, price variability and global food security. *Food Policy* **61**, 9-26 (2016).
308. J. Beckman, C. Estrades, A. Aguiar, Export taxes, food prices and poverty: a global CGE evaluation. *Food Security* **11**, 233-247 (2019).
309. R. Delzeit, M. Winkler, M. Söder, Land Use Change under Biofuel Policies and a Tax on Meat and Dairy Pro ducts: Considering Complexity in Agricultural Production Chains Matter s. *Sustainability* **10**, (2018).
310. S. Fujimori *et al.*, Will international emissions trading help achieve the objectives of th e Paris Agreement? *Environ. Res. Lett.* **11**, 104001 (2016).
311. D. Laborde *et al.*, Agricultural subsidies and global greenhouse gas emissions. *Nat. Commun.* **12**, 2601 (2021).
312. M. Springmann, F. Freund, Options for reforming agricultural subsidies from health, climate, and economic perspectives. *Nat. Commun.* **13**, 82 (2022).
313. A. Gatto, M. Kuiper, C. Middelaar, H. Meijl, Unveiling the economic and environmental impact of policies to promote animal feed for a circular food system. *Resources, Conservation and Recycling* **200**, 107317 (2024).

314. Z. Smeets Křístková *et al.*, European green bonds, carbon tax and crowding-out: The economic, socia l and environmental impacts of the EU's green investments under differ ent financing scenarios. *Renewable and Sustainable Energy Reviews* **211**, 115330 (2025).
315. Y. Jafari, M. Himics, W. Britz, J. Beckman, It is all in the details: A bilateral approach for modelling trade agreements at the tariff line. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie* **69**, 415-442 (2021).
316. K. Calvin *et al.*, Trade-offs of different land and bioenergy policies on the path to ach ieving climate targets. *Clim. Change* **123**, 691-704 (2014).
317. M. Roelfsema *et al.*, Taking stock of national climate policies to evaluate implementation o f the Paris Agreement. *Nat. Commun.* **11**, 2096 (2020).
318. S. Fujimori, T. Hasegawa, T. Masui, K. Takahashi, Land use representation in a global CGE model for long-term simulation : CET vs. logit functions. *Food Security* **6**, 685-699 (2014).
319. S. Fujimori *et al.*, SSP3: AIM implementation of Shared Socioeconomic Pathways. *Global Environ. Change* **42**, 268-283 (2017).
320. Y. Le Page, T. O. West, R. Link, P. Patel, Downscaling land use and land cover from the Global Change Assessment Model for coupling with Earth system models. *Geoscientific Model Development* **9**, 3055-3069 (2016).
321. A. Popp *et al.*, Land-use transition for bioenergy and climate stabilization: model com parison of drivers, impacts and interactions with other land use based mitigation options. *Clim. Change* **123**, 495-509 (2014).
322. B. Elbersen *et al.*, Assessing the effect of stricter sustainability criteria on EU biomass crop potential. *Biofuels, Bioproducts and Biorefining* **7**, 173-192 (2013).
323. M. W. Rosegrant, T. Zhu, S. Msangi, T. Sulser, Global Scenarios for Biofuels: Impacts and Implications. *Rev. Agr. Econ.* **30**, 495-505 (2008).
324. D. Debnath, C. Giner, in *Biofuels, Bioenergy and Food Security,* D. Debnath, S. C. Babu, Eds. (Academic Press, 2019), pp. 61-76.
325. S. Spillias *et al.*, Reducing global land-use pressures with seaweed farming. *Nat. Sustain.* **6**, 380-390 (2023).
326. G. Philippidis *et al.*, Levelling the playing field for EU biomass usage. *Econ. Systems Res.* **31**, 158-177 (2019).
327. T. W. Hertel *et al.*, Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emis sions: Estimating Market-mediated Responses. *Bioscience* **60**, 223-231 (2010).
328. D. Laborde, H. Valin, Modeling Land-Use Changes in a Global Cge: Assessing the Eu Biofuel Ma ndates with the Mirage-Biof Model. *Climate Change Economics* **03**, 1250017 (2012).
329. W. Mauser *et al.*, Global biomass production potentials exceed expected future demand wit hout the need for cropland expansion. *Nat. Commun.* **6**, 8946 (2015).
330. M. Wise, M. Muratori, P. Kyle, Biojet fuels and emissions mitigation in aviation: An integrated asses sment modeling analysis. *Transportation Research Part D: Transport and Environment* **52**, 244-253 (2017).
331. M. J. Walsh *et al.*, Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency. *Environ. Res. Lett.* **11**, 114006 (2016).
332. V. Daioglou *et al.*, Projections of the availability and cost of residues from agriculture and forestry. *GCB Bioenergy* **8**, 456-470 (2016).
333. L. Merfort *et al.*, Bioenergy-induced land-use-change emissions with sectorally fragmented policies. *Nat. Clim. Change.* **13**, 685-692 (2023).
334. T. W. Hertel, U. L. C. Baldos, in *Global Change and the Challenges of Sustainably Feeding a Growing Planet,* T. W. Hertel, U. L. C. Baldos, Eds. (Springer International Publishing, Cham, 2016), pp. 69-84.
335. G. C. Nelson *et al.*, Climate change effects on agriculture: Economic responses to biophysic al shocks. *PNAS* **111**, 3274-3279 (2014).
336. K. Wiebe *et al.*, Climate change impacts on agriculture in 2050 under a range of plausib le socioeconomic and emissions scenarios. *Environ. Res. Lett.* **10**, 085010 (2015).
337. F. C. Moore, U. Baldos, T. Hertel, D. Diaz, New science of climate change impacts on agriculture implies higher so cial cost of carbon. *Nat. Commun.* **8**, 1607 (2017).
338. T. Hasegawa *et al.*, Consequence of Climate Mitigation on the Risk of Hunger. *Environ. Sci. Technol.* **49**, 7245-7253 (2015).
339. R. Wilts, C. Latka, W. Britz, Who is most vulnerable to climate change induced yield changes? A dynamic long run household analysis in lower income countries. *Climate Risk Management* **33**, 100330 (2021).
340. K. Calvin, K. Fisher-Vanden, Quantifying the indirect impacts of climate on agriculture: an inter-m ethod comparison. *Environ. Res. Lett.* **12**, 115004 (2017).
341. A. Snyder, K. V. Calvin, M. Phillips, A. C. Ruane, A crop yield change emulator for use in GCAM and similar models: Perse phone v1.0. *Geoscientific Model Development* **12**, 1319-1350 (2019).
342. J. Maire *et al.,* C. Kondrup *et al.*, Eds. (Springer International Publishing, Cham, 2022), pp. 133-140.

343. D. Klein *et al.*, The value of bioenergy in low stabilization scenarios: an assessment u sing REMIND-MAgPIE. *Clim. Change* **123**, 705-718 (2014).
344. H. C. J. Godfray, D. Mason-D'Croz, S. Robinson, Food system consequences of a fungal disease epidemic in a major crop. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**, 20150467 (2016).
345. T. Chatzopoulos *et al.*, Potential impacts of concurrent and recurrent climate extremes on the global food system by 2030. *Environ. Res. Lett.* **16**, 124021 (2021).
346. C. Elleby, I. P. Domínguez, M. Adenauer, G. Genovese, Impacts of the COVID-19 Pandemic on the Global Agricultural Markets. *Environ. Resource Econ.* **76**, 1067-1079 (2020).
347. S. Osendarp *et al.*, The COVID-19 crisis will exacerbate maternal and child undernutrition and child mortality in low- and middle-income countries. *Nat. Food.* **2**, 476-484 (2021).
348. T. Hasegawa *et al.*, Extreme climate events increase risk of global food insecurity and ada ptation needs. *Nat. Food.* **2**, 587-595 (2021).
349. M. Zhao *et al.*, GCAM-GLORY v1.0: Representing Global Reservoir Water Storage in a Mult isector Human-Earth System Model. *Geoscientific Model Development Discussions* **2023**, 1-45 (2023).
350. P. L. Lucas, D. P. Vuuren, J. G. J. Olivier, M. G. J. Elzen, Long-term reduction potential of non-CO2 greenhouse gases. *Environ. Sci. Policy* **10**, 85-103 (2007).
351. K. Mittenzwei *et al.*, Opportunities and limitations in assessing the multifunctionality of a griculture within the CAPRI model. *Ecological Indicators* **7**, 827-838 (2007).
352. T. Chatzopoulos, I. Pérez Domínguez, M. Zampieri, A. Toreti, Climate extremes and agricultural commodity markets: A global economic analysis of regionally simulated events. *Weather and Climate Extremes* **27**, 100193 (2020).
353. T. Bjørndal, M. Dey, A. Tusvik, Economic analysis of the contributions of aquaculture to future food security. *Aquaculture* **578**, 740071 (2024).
354. T. Heimann, R. Delzeit, Land for fish: Quantifying the connection between the aquaculture sect or and agricultural markets. *Ecological Economics* **217**, 108090 (2024).
355. M. van den Bos Verma, S. Koch, H. Bartelings, S. van den Burg, "The macro-economic effects of increasing seaweed production in the North Sea Region," (Wageningen Economic Research, The Netherlands, 2023). Retrieved from: https://edepot.wur.nl/629904
356. Z. Wang *et al.*, Planned expansion of transportation infrastructure in Brazil has implications for the pattern of agricultural production and carbon emissions. *Sci. Total Environ.* **928**, 172434 (2024).
357. N. Escobar *et al.*, Understanding Uncertainty in Market-Mediated Responses to US Oilseed Biodiesel Demand: Sensitivity of ILUC Emission Estimates to GLOBIOM Parametric Uncertainty. *Environ. Sci. Technol.* **59**, 302-314 (2025).
358. R. Delzeit, T. Heimann, F. Schünemann, M. Söder, "DART-BIO: A technical description," (Kiel Working Paper, 2021). Retrieved from:
359. F. Humpenöder *et al.*, Projected environmental benefits of replacing beef with microbial prot ein. *Nature* **605**, 90-96 (2022).
360. M. Kozicka *et al.*, Feeding climate and biodiversity goals with novel plant-based meat and milk alternatives. *Nat. Commun.* **14**, 5316 (2023).
361. C. Elleby *et al.*, Insects Reared on Food Waste: A Game Changer for Global Agricultural F eed Markets? *EuroChoices* **20**, 56-62 (2021).
362. C. Latka *et al.*, Competing for food waste – Policies' market feedbacks imply sustainabi lity tradeoffs. *Resources, Conservation and Recycling* **186**, 106545 (2022).
363. T. Jansakoo *et al.*, Benefits of air quality for human health resulting from climate change mitigation through dietary change and food loss prevention policy. *Sustain. Sci.*, (2024).
364. D. Laborde, M. Torero, in *Science and Innovations for Food Systems Transformation,* J. Braun, K. Afsana, L. O. Fresco, M. H. A. Hassan, Eds. (Springer International Publishing, Cham, 2023), pp. 105-132.
365. Y. Jafari *et al.*, Can food waste reduction in Europe help to increase food availability and reduce pressure on natural resources globally. *GERMAN JOURNAL OF AGRICULTURAL ECONOMICS* **69**, 143-168 (2020).
366. R. G. Ramos *et al.*, A mathematical programming approach for downscaling multi-layered mult i-constraint land-use models. *International Journal of Geographical Information Science* **37**, 2020-2042 (2023).
367. P. J. Jeetze *et al.*, Projected landscape-scale repercussions of global action for climate a nd biodiversity protection. *Nat. Commun.* **14**, 2515 (2023).
368. S. Fujimori *et al.*, Gridded emissions and land-use data for 2005–2100 under diverse socioe conomic and climate mitigation scenarios. *Scientific Data* **5**, 180210 (2018).
369. E. Ferrari, R. B. Roson, Wolfgang, W. Britz, H. Dudu, An extented myGTAP model to address subsistence production and sub-national households as a module in CGEBox. paper presented at the Conference papers 333059, Purdue University, Center for Global Trade Analysis, Global Trade Analysis Project, 2019.

370. M. Chen *et al.*, Global land use for 2015–2100 at 0.05° resolution under diverse socioe conomic and climate scenarios. *Scientific Data* **7**, 320 (2020).
371. P. Van Ha, T. Kompas, H. T. M. Nguyen, C. H. Long, Building a better trade model to determine local effects: A regional a nd intertemporal GTAP model. *Econ. Modelling* **67**, 102-113 (2017).
372. A. Bouët, D. Laborde, US trade wars in the twenty-first century with emerging countries: Mak e America and its partners lose again. *World Econ.* **41**, 2276-2319 (2018).