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Abstract

Achieving food and nutrition security for all in a changing and globalized world remains a critical challenge of utmost importance. The development of solutions benefits from insights derived from modelling and simulating the complex interactions of the agri-food system, which range from global to household scales and transcend disciplinary boundaries. A wide range of models based on various methodologies (from food trade equilibrium to agent-based) seek to integrate direct and indirect drivers of change in land use, environment and socio-economic conditions at different scales. However, modelling such interaction poses fundamental challenges, especially for representing non-linear dynamics and adaptive behaviours.

We identify key pieces of the fragmented landscape of food security modelling, and organize achievements and gaps into different contextual domains of food security (production, trade, and consumption) and at different spatial scales. Building on in-depth reflection on three core issues of food security – volatility, technology, and transformation – we identify methodological challenges and promising strategies for advancement.

We emphasize particular requirements related to the multifaceted and multiscale nature of food security. They include the explicit representation of transient dynamics to allow for path dependency and irreversible consequences, and of household heterogeneity to incorporate inequality issues. To illustrate ways forward we provide good practice examples using meta-modelling techniques, non-equilibrium approaches and behavioural-based modelling endeavours. We argue that further integration of different model types is required to better account for both multi-level agency and cross-scale feedbacks within the food system.

Keywords: food security; multi-scale interactions; model integration; agent-based models; economic equilibrium models; crop models; social-ecological feedbacks; land use

1 Introduction

Given competing pressures on land and other environmental resources, the food security challenge requires innovative solutions to mitigate trade-offs between environmental and social objectives while balancing short and long term development (Riahi et al., 2017; Hasegawa et al., 2018). Success in sustainably achieving food security for all can be supported by insights obtained from science-based modelling of the complex interactions among factors influencing food security across scales in a complex adaptive system (e.g. Antle et al., 2017a). We understand scale as the combination of spatial, temporal, and analytical resolution and extent (see also Gibson et al. 2000). The 'micro' scale is then characterized by high resolution and small extent and the 'macro' scale by low resolution and large extent; scales may consequently range from the global to the household and transcend traditional disciplinary boundaries.

The imperative for multiscale analysis of the food system can be aptly illustrated with the case of the US Renewable Fuels Mandate. Early systems analysis by environmental and energy systems engineers found that corn ethanol production in the US could reduce life cycle greenhouse gas emissions (Farrell et al., 2006). This was based on detailed analysis of direct emissions associated with the growth of the crops as well as those tied to transportation, processing and delivery of the product to consumers.

However, the absence of any link to market modelling of agriculture and land use change led to the omission of the indirect impacts of diverting a substantial share of food production into the energy markets. Once this component was brought to bear, this government programme was found to have adverse impacts, both on the environment and on food security (Searchinger et al., 2008), that can be related back to the market effects of this policy (Hertel and Tyner, 2013). If early analyses had been based on a multiscale model, the programme might never have gained such overwhelming political support.

Achieving the transition towards sustainable food systems based on such multiscale analysis faces further challenges, particularly in many low and middle income countries. These include a rapidly growing urban and rural population, limiting and poorly functioning market infrastructure, limited nutrient inputs and poor crop management resulting in large yield gaps (Lobell et al., 2009; van Ittersum et al., 2013) and degradation of soil quality and associated ecosystem services. Further challenges are related to climate change, food wastage, water scarcity, and changing lifestyles leading to a higher demand for animal-based food products (Godfray et al., 2010). At the same time, other drivers of change include the spread of information and communication technologies, vertical coordination in supply chains, and rising import competition. The dynamics of land use change also plays a role, influencing livelihoods, human health and nutrition, and the environmental and institutional foundations upon which these depend. While the full effect of these changes may be some years away, there is evidence that rural and urban communities are already undergoing rapid transformation (e.g. Jayne et al., 2016; Fraval et al., 2018).

In addition to these macro-scale challenges and drivers, food security depends on household access to adequate food (see FAO, 1996, but also Coates, 2013 and Headey and Ecker, 2013) and is, from this perspective, largely an outcome of local-scale processes. Sufficient total global food production does not necessarily ensure food security for the entire population. Nutrition security therefore complements the concept of food security by considering one’s ability to meet nutritional needs through food intake. Nutrition security is commonly assessed at the individual level, where pro-male and pro-adult biases have frequently been observed within households (Coates, 2013). Nevertheless, indicators of food and nutrition security are commonly aggregated to regional, national, and global levels for the purpose of policy assessment (Herrero et al., 2017). In this paper, we generally use ‘food security’ to mean food and nutrition security across scales.

In the exploration of possible development pathways and their associated consequences, macro-scale impact assessment models are currently in widespread use. These models typically simulate global scenarios and explore large-scale consequences of policy options (e.g. Riahi et al., 2017). The mismatch of scales and approaches between macro-level modelling and locally-determined processes and indicators makes it difficult to answer critical questions, including: How can we better account for food security when analysing long-term trends occurring at large scales (like economic development, population growth, and water scarcity)? How can we quantify the trade-offs between different indicators when searching for a sustainable future (e.g. van Wijk, 2014)? How resilient is the food system in delivering appropriate nutrition under a range of shocks, e.g. extreme weather or geo-political instability (Tendall et al., 2015; Urruty et al., 2016)?

Answering these questions poses fundamental challenges, since the underlying agri-food system is characterized by interactions across scales that show non-linear dynamics and adaptive behaviours. The wide variety of models that aim to integrate land use, environment, and food security highlights the existence of different drivers of change related to distinct phenomena. These models range from the global scale (e.g. food trade equilibrium models) to the local scale (e.g. farm-level crop models, bio-economic models or agent-based approaches) (van Wijk et al., 2014). Models have been developed for different purposes and typically address only selected aspects of food security from a specific point of view, ranging from agricultural science (e.g. Troost et al., 2015) and (agricultural) economics (e.g., van Ittersum et al., 2016, Baldos & Hertel, 2015) to systems science (e.g. Hammond and Dube, 2012), and thus have different and often incompatible conceptual bases.

Models that address food security issues operating across multiple scales often work either through local-level proxies when analysing large-scale processes (for example through single crop yield response functions or a single farming systems representation for a given geographical zone, e.g. Hasegawa et al., 2018), or using global drivers when analysing local processes (for example through commodity prices or farm size development scenarios, e.g. Herrero et al., 2014). More recently, analyses at global or regional level have made transdisciplinary progress in finding solutions that take more account of people's local reality (e.g. Ermolieva et al., 2017; Antle et al., 2014). Examples exist in which interactions between drivers of food security at different levels have been assessed (e.g. van Ittersum et al., 2008; Laborde et al., 2016; Ruane et al., 2018). These models are a first step towards the multi-scale representation of land use, environment, and food security, but they still lack a more complete reconciliation of processes across scales to capture relevant feedbacks (see also van Wijk, 2014).

We argue that by narrowing the gap between the micro and the macro scale, combined with a better consideration of food-system-specific (multi-level) agency and feedbacks, it is possible to improve the representation of food security-relevant processes and indicators in large-scale models and thus advance the current state of food system models. We emphasize special requirements of the multifaceted and multiscale concept of food security and argue that further integration of different model types is required to better account for both multi-level agency and cross-scale feedbacks within the food system.

We draw from the current state of food security modelling to identify achievements and gaps in different contextual domains of food security (production, trade, and consumption) at different spatial scales (local, regional, and global). Three core issues of food security are extracted for further in-depth reflection and analysis. Finally, we use these core issues to consider strengths and weaknesses of methodological approaches currently in use and identify promising ways forward.

2 Current State of the Art of Food Security Modelling: Achievements and Gaps

Research on food security modelling is composed of a fragmented literature and methodology, characterized by individual efforts in disparate disciplines with relatively few interconnections. Although many literature reviews are available on the different types of modelling that might be, or have been, applied to examine agro-economic or food-related issues (e.g. van Tongeren et al., 2001; Ciaian et al., 2013; Francois and Martin, 2013; Kelly et al., 2013; Millington et al., 2017; Huber et al., 2018, some addressing food security: van Dijk and Meijerink, 2014; van Wijk, 2014; van Wijk et al., 2014; Brown et al., 2017), a comprehensive, interdisciplinary, multi-scale overview of food security modelling does not exist in the current body of literature. To address this gap, we begin by providing a summary of the modelling approaches that have been applied to examine aspects of food security, before reporting on achievements to date and the outstanding challenges.

Food security, as defined by FAO, 1996, consists of four key elements (cf. also FAO, 2014): physical availability of food; economic and physical access to food; food utilization; and the stability of these three dimensions over time. Of these, availability and access to food have been most thoroughly described, with new approaches currently being developed to better address utilization and stability.

In the following, we do not directly use these four pillars, but instead emphasize three primary components of food security reflected in contemporary models: food production, trade, and consumption. The interplay of these components is key to the challenge of feeding future global populations (Godfray et al., 2010). We also discuss the stability dimension of food security which requires dynamic models with high temporal resolution of economic and biophysical aspects (such as commodity market volatility or pest occurrence and diffusion). Utilization of food is generally poorly represented in modelling approaches and thus not considered here.

2.1 Modelling Approaches

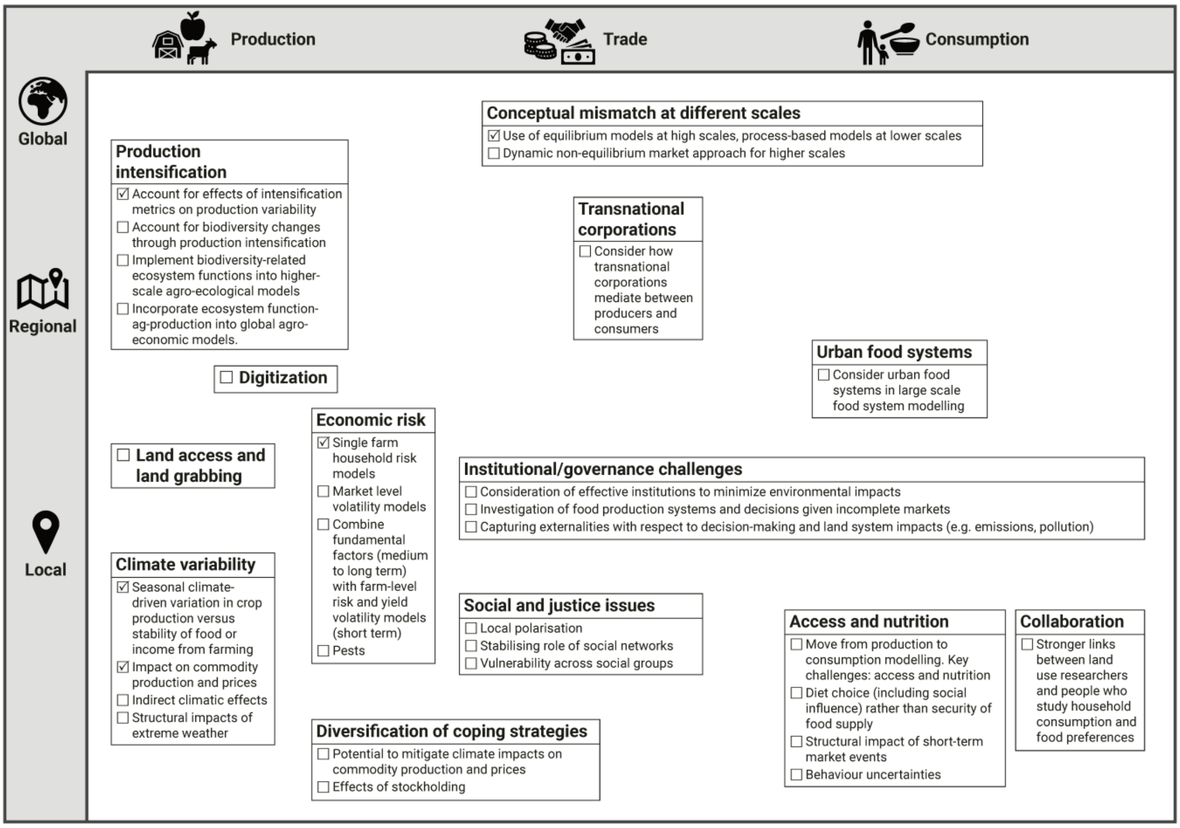
Numerous approaches exist that are relevant to modelling food production, trade and consumption. Agricultural production is a key aspect of food security modelled in multiple ways, including bio-economic models (typically describing land use through optimizing an objective function like profit, e.g., Janssen and van Ittersum, 2007), process-based land use models (describing the development of land use and interactions with other factors over time through functional relations, e.g. Brown et al., 2013; Verburg et al., 2016), multi-agent models (focusing on interactions between land users and/or farmers' heterogeneity, e.g. Bharwani et al., 2005; Matthews et al., 2007; Ding et al., 2015), transition-rule-based approaches (representing the transition between different states of the land, e.g. Bestelmeyer et al., 2017 for rangelands) and econometric/statistical models (empirically describing relationships between drivers of all different sorts and consequential land use, e.g., Munroe et al., 2002; Millington et al., 2007). Models from different disciplines (e.g. economics, agronomy) tend to have a different representation of core concepts, data types and state variables in space and time. The following types of models simulating food production have been the workhorses for ex-ante analysis and priority setting for the deployment of technological interventions and for examining trade-offs related to the use of natural resources: (a) Biophysical crop models (for an overview see Müller et al., 2017b), (b) farm management models (e.g. FSSIM, Louhichi et al., 2010, IFM-CAP, Louhichi et al., 2018, also see Janssen and van Ittersum, 2007 and van Wijk et al., 2014) and (c) static and dynamic economic models (e.g. CAPRI, Fellmann et al., 2018; AgriPoliS, Happe et al., 2006). In the integrated modelling framework SEAMLESS-IF, an effort was made to link these types of models across scales in Europe (van Ittersum et al., 2008; Ewert et al., 2009).

Moving from production to consumption requires a consideration of trade. Computable general and partial equilibrium models have been used widely to examine how changes in policy or environmental conditions could influence trade in agricultural and food commodities, both globally and regionally. Well-established modelling frameworks such as GTAP (Aguiar et al., 2016) incorporate large databases to simulate flows of goods between countries and regions by representing bilateral trade, transport, taxes and subsidies. Equilibrium approaches have also been incorporated into integrated modelling frameworks such as IMPACT (Robinson et al., 2015) to interact with climate, crop simulation and other models to examine scenarios of environmental, socioeconomic, technological and policy change. Less widely used, system dynamics approaches use non-equilibrium representations of feedback loops composed of stocks, flows, and information propagation, and have been used to represent the impacts of land use on global trade (e.g. Warner et al., 2013). Agent-based approaches representing individual countries as decision-making entities are also being developed to simulate trade and facilitate understanding impacts of national policies on food security and food-related civil unrest (Natalini et al., 2017).

On the consumption side, food allocation within and across households is critical to food security. Agent-based approaches are increasingly used to assess food security of smallholders in developing countries over time (e.g. Dobbie et al., 2018 which explicitly considers the four dimensions of food security at the household and village level for a case study in Malawi). In a developing country context, recent agent-based models (ABMs) analyse healthy food choices of consumers capturing interactions between retail location, social networks and income (Tracy et al., 2018 pp. 82-83). Equilibrium models are uniquely positioned to assess commodity and factor price impacts of perturbations to agricultural supplies, technologies and policies (e.g. Hertel et al., 2007; Nelson et al., 2014a). These price outcomes are critical in determining the consequences for earnings, consumption, and thereby food security. By definition, these outcomes refer to a specific time period over which demands adjust to changes in supply and vice versa. Equilibrium models may be paired with micro-simulation models in order to determine household impacts of these types of shocks (e.g. Hertel and Winters, 2005; Cockburn, 2006; Cogneau and Robilliard, 2007).

2.2 Representing the Food Security Context in Models

To present achievements and challenges in food security modelling, we consider food production, trade, and consumption, across three spatial scales (Figure 1). While we acknowledge that stability (temporal scale) is a critical dimension of food security (cf. Mehrabi et al., 2019; Renard and Tilman, 2019), we do not represent explicitly it in Figure 1, but assume that stability is an underpinning requirement in all depicted elements.



Climate-driven variability of crop yields has a large influence on the stability of food production at local to regional scales, constituting an important source of risk to subsistence farmers and low-income groups. Crop models are continuously developed to better capture seasonal and inter-annual yield variability as driven by weather and extreme events (Maiorano et al., 2017; Schauberger et al., 2017; Webber et al., 2018), but the applicability of crop models in integrated assessment studies is still considerably constrained (Ewert et al., 2015). Additionally, landscape-scale ecological properties and processes are most frequently neglected in food security modelling studies, including interactions across multiple trophic levels of food webs and trade-offs with biodiversity (van Noordwijk, 2002). A classic example for this is pollination. The presence of pollinating species is substantially promoted by heterogeneously structured landscapes (Klein et al., 2007; Kremen and M'gonigle, 2015; Kovács-Hostyánszki et al., 2017). A sufficient abundance of animal pollinators is critical for many crops that provide vital micro-nutrients to humans (Eilers et al., 2011). An additional challenge lies in the currently observable mismatch between models representing biophysical and socioeconomic processes (cf. also Evans et al., 2013; Verburg et al., 2019).

Climate variability also affects farmers' income. While many agricultural sector and market models can consider impacts of climatic change on commodity prices (Nelson et al., 2014a; Nelson et al., 2014b; Balint et al., 2017; Hasegawa et al., 2018; van Meijl et al., 2018), they generally do not consider short-term variability from extreme events (with notable exceptions, cf. Schewe et al., 2017). They are also generally unable to capture the economic impacts of such shocks, together with other abrupt social and economic events, for example in limiting investments in agricultural technologies (Kalkuhl et al., 2016; Cottrell et al., 2019). Similarly, many indirect effects, including migration, changes in land tenure, strategies to cope with income shortfalls, and speculation on food prices, are also neglected.

Medium- to long-term developments also matter when assessing producers' reactions to risks, not least in terms of adaptive responses to ameliorate or benefit from the effects of climate change. Beneficial opportunities related, for instance, to the adoption of new crop types that better suit emerging climatic conditions are rarely modelled (cf. Holman et al., 2019), and when they are included, they typically do not distinguish between intensification and adaptation, simply resulting in an upward shift of production across all climates (Lobell, 2014; Moore et al., 2017). The different capabilities of producers to cope with risk and volatility can lead to local polarization in wealth, but is seldom considered in modelling studies (for exceptions cf. Dressler et al., 2018 or models focussing on poverty traps, cf. Zimmerman and Carter, 2003). The same holds for the integration of informal risk-sharing networks, the application of technology, or income diversification through trade activities, stock-holding, and remittances sent by relatives who have emigrated (Rockenbauch and Sakdapolrak, 2017). Altogether, this reveals a gap in reflecting food-related social and justice issues in modelling.

A major gap in modelling is digitization of production systems (for current reviews on the relevance of big data and digitization in agriculture cf. Bronson and Knezevic, 2016; Antle et al., 2017b; Wolfert et al., 2017; Weersink et al., 2018). On the one hand, precision farming promises an increase in yields and reduced environmental stress from pesticides and fertilizers; on the other, dependency on high-tech methods may exacerbate social inequalities or change power relations (Maru et al., 2018). Spanning local to regional extents, issues of land access and land grabbing are highly relevant topics as secure access to arable land is vital to food security, particularly for smallholders (Holden and Ghebru, 2016). To date, modelling has rarely been used to show the extent of such practices and their impacts on food security. Efforts exist to conceptualize land tenure security from an interdisciplinary, dynamic equilibrium perspective (Simbizi et al., 2014) and empirical analyses are repeatedly performed, showing the relevance for productive investments (for a newer example see Fitz, 2018). However, parameters in larger scale models analysing food security take the current tenure system as given. This may be due to the context and country specific nature of tenure system impacts and the absence of endogenous investments in many models. Equilibrium models at larger scales simply do not have a comparative advantage for analysing such national changes in governance (on the limited incorporation of governance in models in general see Wang et al., 2016).

While consumption closely relates to production activities and incomes for many smallholder farmers, we consider it separately here, with a focus on access and nutrition, affected by heterogeneous behavioural dynamics. Both developing and developed countries' specific risks of malnourishment are under-represented in food security models, with limited consideration of nutrient deficiency or obesity (for an exception, see Springmann et al., 2016) or differing vulnerability to price shocks of urban consumers and rural producers. However, their representation will require collaboration with empirical experts who study household consumption and food preferences, as well as sources of household income (Ahmed et al., 2009). Beyond individual consumption, which is largely governed by individual resources and behaviours as influenced by social norms, transnational corporations have recently emerged as key entities leading to increased commercialization and concentration in global food chains (Gibbon and Ponte, 2005), with few exceptions (Sitko et al., 2018). Economic models rarely represent these corporations' role in directing market activity although they take over a crucial part of agency in real markets. Likewise, urban food systems have been given limited attention in terms of modelling (cf. Bodirsky et al., 2015 as an exception, where urbanization is discussed as a driver for modelling diets). Finally, food security challenges are also institutional: topics such as health, environmental protection, governance, and externalities can hardly be handled properly by models based solely on market calculations, even more since they vary in time, space, and across societies (for an exception, see Wang et al., 2016). In this respect, it is often the capabilities of current models that drive modelling exercises, rather than requirements of the food security issue.

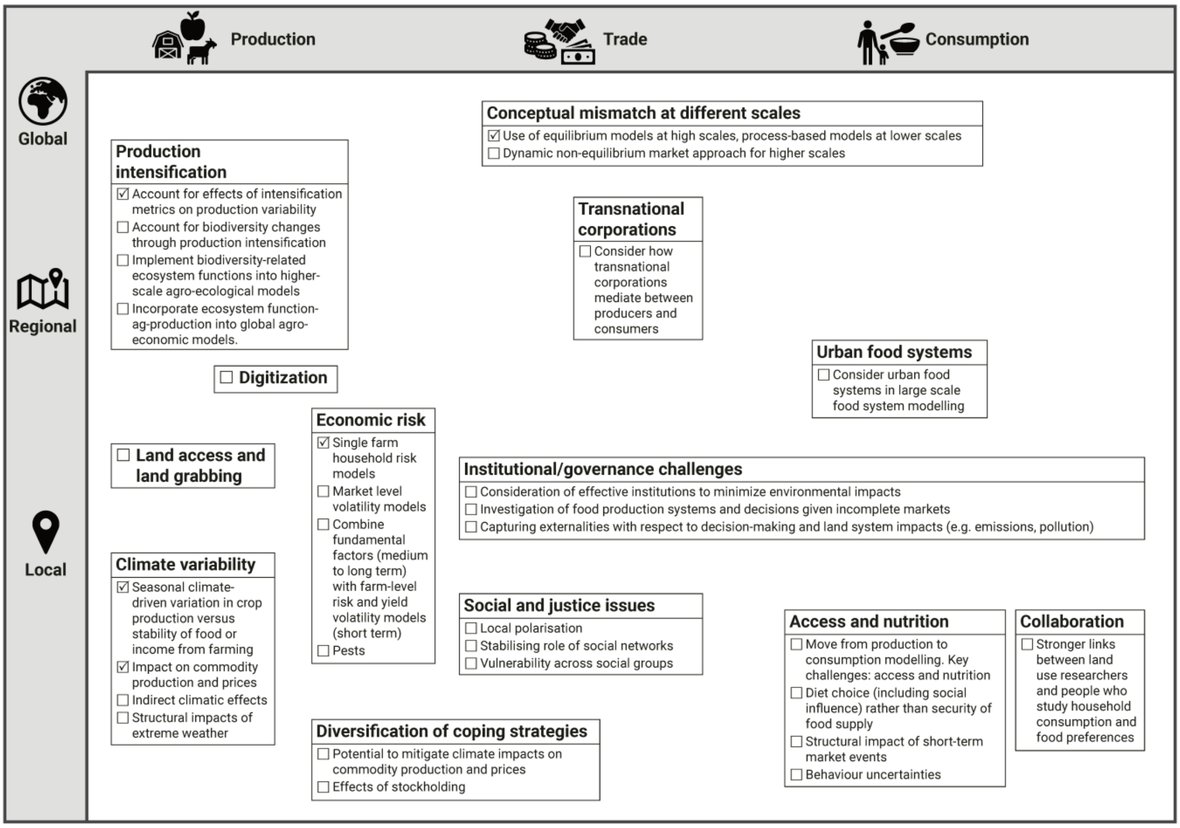


Figure 1: Aspects of food security modelling. They are arranged by spatial scale (y axis) and three key components of food systems (x axis). The temporal dimension is not represented here. We omitted several aspects (e.g. health, cultural dimensions, and non-spatial scales such as institutional scale, cf. Preston et al., 2015) in favour of clarity. Topics may span multiple levels. Most bullet points are about open questions, denoted by squares. Checked boxes, on the other hand, denote that these have been adequately addressed by modellers.

3 In-depth Reflection and Analysis for Three Core Issues

From our overview of achievements and gaps summarized in Figure 1, we identified three core issues for in-depth reflection and analysis. These issues – volatility, technology and transformation of the food system – embody distinct core components of food security and correspond, respectively, to short-, medium- and long-run adaptations to food insecurity. They serve to illustrate particular challenges related to the micro-macro scale connection. For each core issue, we point out central mechanisms to be included in models and present the current state of the art.

3.1 Volatility: Uncertainty in Supply and Prices

Uncertainties in commodity supply (e.g. due to extreme weather events or pests) can lead to instabilities in food prices which are transmitted globally through markets. With little short-run potential to adjust crop planting and technological choices, weather-induced yield variability can dramatically impact prices, and hence the affordability of food (Wiggins and Keats, 2013). This problem is particularly severe for urban residents and others who are net food buyers. To address these issues, models need to incorporate processes such as storage and transportation (trade) to better characterize the potential for mitigation of food price volatility (Wright, 2011; Burgess and Donaldson, 2010). Medium- to long-term adaptations by consumers, producers, investors, policymakers and actors in the value chain to manage increased risk exposure might in turn affect short-term volatilities, as intensification of crop production has an impact on its stability (Müller et al., 2018). Risk-coping strategies such as formal and informal insurance and income diversification also need to be taken into account.

Agricultural markets are vulnerable to uncertainties in supply, since production hinges on uncertain weather conditions as well as environmental hazards such as pests. This is a complex modelling challenge as weather effects can be highly localized, but the market outcomes represent the aggregation of these local variations. Diffenbaugh et al., 2012 reproduced national historical yield volatility in US maize production using fine-scale climate model output and crop production information, linked through a non-linear yield response to temperature and precipitation estimated by Schlenker and Roberts, 2009. Diffenbaugh et al., 2012 were able to replicate aggregate price volatility using this approach. They show that climate-driven, supply-side uncertainty is likely to increase under future climate due to more frequent exceedances of critical temperature thresholds. The consequences for commodity markets in the face of price-inelastic demands are potentially severe. Where storage is possible, price swings can be mitigated by agents taking advantage of those swings to buy low, store the commodity, and sell when supplies are low and prices high (Roberts and Tran, 2012). However, in the poorest countries of the world, pests, cash flow constraints and other factors result in considerable storage losses, leading to lower storage rates (Kaminski and Christiaensen, 2014). In much of Africa producers sell their harvest at low prices and end up buying back grains at high prices during the ‘lean season’. Introduction of low cost, improved storage technologies can have a positive impact on household welfare in this context (Murdock and Baoua, 2014). It can also promote the adoption of new crop varieties which are high yielding, but more vulnerable to pests (Ricker-Gilbert and Jones, 2015).

The combination of climate and price variability can be particularly problematic for low income, net food buyer households. This emphasizes the importance of household heterogeneity which is well represented through ABM. For example, Wossen and Berger, 2015 developed an ABM for Northern Ghana, where regional climate models are projecting significant warming. They analysed the distributional consequences of climate variability on rural households and found that the provision of agricultural credit and improved access to off-farm employment are particularly effective ways of mitigating the impacts of future climate variability on low-income households in this region. A broader picture is provided by a review on different types of farm household models to analyse food security under climate change by van Wijk et al., 2014.

One important means of dealing with climate variability is insurance. Informal insurance through extended families and social networks (Rockenbauch and Sakdapolrak, 2017) is widespread in many developing countries, as is the sale of assets including livestock. However, these traditional methods of insurance against unanticipated events are ill-suited to co-variate climate shocks, which tend to affect the entire community/region (Dercon, 2005). In light of this, index insurance tied to regional weather outcomes is a response which has been offered with great enthusiasm by some in the development community. If it is publicly provided, it tends to have low transactions costs, more rapid pay outs and it minimizes asymmetric information challenges (Giné et al., 2008; Cole and Xiong, 2017). Yet the poor have historically been slow to adopt insurance, even where such markets exist (Kiviat, 2009). While there has been some progress on the adoption of micro-insurance across the developing world (http://worldmapofmicroinsurance.org/), this is an area ripe for further exploration where intended and unintended consequences need to be analysed (cf. Müller et al., 2017a for a review of modelling and empirical studies of the impacts of agricultural insurance). Economic modelling studies have been used on the farmer level (cf. Ricome et al., 2017) and on the financial market level (cf. Carter et al., 2016) for studying the impact of insurance on land-use strategies or on technology adoption. It would seem that agent-based models which focus on inter-household interactions and/or more sophisticated representation of farmer decision making might be able to shed additional light on the constraints and opportunities for more widespread use of index insurance (for first attempts, see Müller et al., 2011 and John et al., 2019 on the impact of insurance on pastoral land use strategies and possible side effects).

Another vehicle for adaptation to supply uncertainties and the ensuing price volatility is improved transport. Burgess and Donaldson, 2010 used an equilibrium trade model to demonstrate how the introduction of railroads in colonial India dramatically reduced famine in the wake of failed monsoons. Porteus, 2015 studied the consequences of high trade barriers within the African continent using a dynamic equilibrium model. He found that lowering these trade frictions to levels observed in the rest of the world would reduce the average food price index by almost 50%. In addition, he concluded that lower trade costs will promote the adoption of new agricultural technologies, as early adopters gain access to a larger market. Deeper investigation of the interplay between market structures and the adoption of technology by heterogeneous farm households is another fruitful area for integration of ABMs with market equilibrium models.

It is not just physical infrastructure that can play a role in mitigating the impact of volatile commodity supplies on food insecure households. Socio-political and economic considerations are equally important. Open borders allow international trade to mitigate the impacts of crop failure (Verma et al., 2014). More generally, stable governance is critical for ensuring food security. Indeed, civil strife is one of the main factors behind many of the famines in Africa over the last two decades affecting production as well as distribution (Africa Center for Strategic Studies, 2017). And, unfortunately, a changing climate can increase the likelihood of civil strife (Burke et al., 2009). Capturing this feedback from climate to food insecurity, to civil strife, and back to food insecurity is a challenge that could be further explored within an ABM framework.

Analysis of food security in the presence of supply uncertainties can give rise to complex models with many different choices for added sophistication. Future work might usefully focus on the nexus of economic modelling of markets and ABMs. Such an approach could offer a better representation of how heterogeneous agents respond to volatility under different institutional and cultural contexts (e.g., by taking up new technologies or transforming production and marketing systems, cf. next sections and Berger et al., 2017).

3.2 Technology: Dealing with Heterogeneous Innovation Spread

Technological innovation and diffusion across different domains of the food system (production, marketing and trade, as well as consumption) is highly relevant to food security in the medium to long term. Technology development including breeding and crop management has been the key driver of productivity increases in the past and will be the most important driver for the future (Ewert et al., 2005). In the face of increasing risk of supply shocks, agents in the food system would be expected to adopt new technologies to adapt to new climatic conditions and mitigate the impact of extremes on land use and productivity. Adoption rates vary according to decision-making characteristics such as risk aversion, so that understanding the household level impacts requires models that capture the relevant agent heterogeneity, at individual or typological level (Daloğlu et al., 2014; Brown et al., 2019). Technology can also facilitate improvements in transport, marketing and storage. Technological innovation is generally a process driven by private incentives to achieve higher productivity producing more or better goods and services with fewer inputs (resources), and by public institutions aiming to improve (agricultural) productivity to ensure long-term food security.

R&D spending creates “knowledge capital”, which drives productivity growth through technological innovation. However, the capability to translate these investments into productivity gains varies widely across the world. In a recent paper reviewing 44 empirical studies, Fuglie, 2018 finds that a 1% increase in overall R&D capital leads to a 0.67% increase in agricultural output in developed countries but only 0.38% in developing countries (0.17% in Sub-Saharan Africa). Dietrich et al., 2014 propose a modelling approach in which the costs of R&D for yield increases depend on the current intensity level. Spillovers across regions and R&D categories (public and private) as well as accumulation and depreciation of R&D capital over time creates complex spatio-temporal dynamics requiring appropriate modelling tools to understand how public R&D spending influences agricultural productivity and thereby the availability and accessibility dimensions of food security in the long run.

Returns on R&D expenditure are therefore uncertain. Baldos et al., 2019 show that returns to public R&D materialize slowly, taking one to three decades for their largest impact to be felt in productivity gains. Such long lags in realizing agricultural output growth from R&D spending creates short-term irreversibility and the need to act early in order to prepare for uncertain future developments. Cai et al., 2017 call for significantly increased R&D spending at the global level in the first half of this century to prepare for the possibility of high population levels and climate change impacts on productivity in the second half. Region-specific analyses are crucial for assessments of the impact of innovation on food security and would require distinct identification of regional R&D spending versus its spillovers. Relating investments in agricultural technology to food security, Mason-D'Croz et al., 2019 find that spending an additional $15 billion per year between 2015 and 2030 would reduce the share of people at risk of hunger by more than half.

Global-scale research on the relationship between R&D and productivity shows that investment in technology matters for food availability and access. However, it does not say much about the role of the private sector and the impacts on heterogeneous actors. Digitization and automation may provide technologies that fundamentally transform modern agricultural management without being “policy induced”. The speed, level and spatial expansion of technology uptake by actors in the supply chain is relevant for the macro-(market-)level and in turn feeds back to the adoption process (cf. Brown et al., 2018a for empirical evidence for knowledge diffusion patterns in land use). Current integrated assessment models that assume immediate uptake have been criticized as unrealistic (cf. Turner et al., 2018). Closely related to the dynamics and spatial aspect of the diffusion process are questions like: Who might gain access to these new technologies? Why might they choose to adopt them (or not)? Will the technologies deliver their intended benefits 'in the field'? And who are subsequent winners and losers from these developments?

A multitude of empirical, typically econometric studies on technology adoption at farm level exist, scrutinizing the determinants leading to adoption (Wu and Pretty, 2004; Knowler and Bradshaw, 2007; Baumgart-Getz et al., 2012; Genius et al., 2013; Meijer et al., 2015; Xiong et al., 2016). The empirically relevant determinants go beyond the comparative 'profitability' of these technologies and include a variety of cognitive, behavioural and social factors. These are often conceptualized by modern theories borrowing from the social psychology discipline such as the 'theory of planned behaviour' (Ajzen 1991). Attitudes, perceived control, risk, social network interaction and more all play a role to embrace or reject new production practices (Marra et al., 2003; Llewellyn, 2007; Maertens and Barrett, 2012). Models that endogenously represent technological change and assess the potential impacts need to be careful in representing behavioural mechanisms that determine adoption (Dessart et al., 2019). This is especially true if the representation of heterogeneity over space and time is targeted, but also to achieve accuracy in aggregate uptake and impact (Lambin et al., 2000; Alexander et al., 2017).

Although this empirical literature acknowledges dynamic and spatial feedbacks through networks and the development of supply chain structures, the formal modelling of such dynamic, spatially explicit systems seems in its infancy (for examples from the agricultural domain and beyond, see Berger, 2001; Kiesling et al., 2012; Brown et al., 2018b). This is especially the case in large-scale models that are relevant to food security issues, but require generalizations of the kind that are not yet established in the literature on the adoption of technological innovations in agriculture. Fundamental technological transformations are crucial to many of the 'pathways' towards international policy objectives such as the Paris Agreement on climate change mitigation, making an assessment of their adoption and effects important for policy support (van Vuuren et al., 2015; Rogelj et al., 2016; Walsh et al., 2017).

A detailed "bottom-up" model representation of endogenous technological change faces substantial challenges. Conceptual differences arise within and between dynamic modelling systems at the local scale and equilibrium models at larger scales regarding the length of the time horizon, the implicit (by production factor variability) or explicit (by time steps) definition of time, the spatial coverage, and the resolution of product and production activities. A key question is what type of "bottom-up" modelling of technological change – if any – is capable of adequately informing larger scale models with respect to spatial and temporal differentiation. Given the current limited experience, smaller scale models may be better placed to initially explore the behavioural and social elements identified and experiment with different representations to account for various theories and contexts. Section 4 discusses promising strategies for linking large-scale with small-scale models, which explore behavioural and social aspects.

3.3 Transformation: Moving to a Food Secure World?

Radical and rapid transformative change of food production (and consumption) systems is possible. Yao, 2000, for example, documents the economic reforms in China of Deng Xiaoping, starting in 1978, which in six years increased grain production by a third and doubled real per capita incomes. Achieving global food security, especially if we are to avoid increased environmental harm, will require transformative change of a kind that may entail hitherto unimagined technology and social institutions.

Such transformative change poses a significant challenge not only for policy and society, but also for modelling. Only recently have initial conceptual studies been published that investigate changing institutions such as social norms or collective governance, mostly through agent-based or network approaches (cf. Gräbner, 2016; Ghorbani et al., 2017; Scott et al., 2019).

Transformative change is challenging to model because, in its most significant form, it can radically change the way the system is conceptualized. Not only do the values of state variables change, but the structure changes too: different variables, processes, classes, individuals, and relationships need to be included for the dynamics of the new system to be adequately represented (Müller et al., 2014, Polhill et al., 2016; Donges et al., 2018; Köhler et al., 2018). As may be appreciated, endogenously generating such new elements of model structure as part of model function is far from trivial. Hence, transformative change is typically modelled exogenously using scenarios (e.g. in integrated assessment models at the macro scale, cf. van Vuuren et al., 2018) or by comparing dynamics under different parameters. Model structures in such models are designed such that they anticipate the consequences of future change. Insofar as endogenous transformative change entails ideas that have not yet been conceived, our ability to represent such concepts in models is obviously further curtailed. As a result, modelled forecasts of the outcomes of transformative change are, for understandable reasons, biased.

Thus, modelling is often constrained not only by observed data (e.g. for calibration and validation) but also by observed structures. Although some models endogenize technological change as an investment in improving production without necessarily specifying what the technology is (Dietrich et al., 2014; Baldos et al., 2019; Mason-D'Croz et al., 2019), radical technological change involving more than incremental improvements can provisionally be conceptualized as an exogenous disturbance to the system. Since technology is discussed in depth above, we concentrate here on social aspects of transformative change.

Avelino et al., 2019, p. 196 introduce the concept of Transformative Social Innovation (TSI) as “social innovation that challenges, alters or replaces dominant institutions in the social context.” They emphasize the co-evolutionary, multi-actor, multi-scale nature of TSI, bringing together social innovation (“new ways of doing, organizing, knowing and framing”), system innovation (new institutions and infrastructure), game-changers (significant macro-level changes that “change the rules” of societal interaction), and narratives of change (the local and global discourse on change, which act to spread, focus, counter and frame understandings of change).

As an illustration, we can consider how assessing food security based on economic models often fails to account for distributional issues. Modelling the exchange of food based on price, for example, implies that access to food is determined by the money people have. Although non-price-based food distribution does not currently prevail globally, it might one day emerge. Were such a system successful, it would meet all the criteria of TSI, but modelling its emergence is challenged by the fact that we do not even have the vocabulary to describe it, never mind data, functions or algorithms to simulate its processes. We struggle to model social transformation also because our models are embedded in current social systems. It might be insufficient to add a few fixes to the current system if the fundamental principles on which it runs will not allow sustainable global food security to be achieved. While modelling may serve as a valuable experimental tool before actually implementing a transformation, modelling transformation processes is a fundamental challenge.

This limitation of most current models is addressed by Holtz et al., 2015 in their review of the prospect for modelling societal transitions. As a possible solution, they propose following Andersson et al., 2014’s suggestion that the required changes in ontology need to be embedded in the dynamics of the model. By ontology, we refer to an explicit description of concepts and relationships in a domain of interest (Gruber, 1993) that could be understood as the model's structure. Such changes are more difficult to implement when modelling future, rather than reconstructing past, transformations. Commenting on Holtz et al., 2015, McDowall and Geels, 2017, develop ten challenges. One of these challenges (McDowall and Geels, 2017, p. 43) returns to the issue of structural change and offers an alternative interpretation of Andersson et al., 2014's challenge of 'wicked systems' (both complex and complicated) to modelling: that formal approaches are intrinsically limited, and narrative theories are better suited.

The challenge of modelling ontological change in the study of transformations remains. One participatory approach is offered by García-Mira et al., 2017. They use backcasting workshops (Quist and Vergragt, 2006) to develop scenarios of transitions to lower-carbon workplaces, which they then explore with an agent-based model that is empirically calibrated using questionnaire data. Backcasting workshops entail envisioning future change, and then working backwards to the present day to consider the structural changes needed for each imagined future to occur. The results are narratives of transformations to possible futures, and provide one way of eliciting the kind of knowledge needed to include ontological change in a simulation model addressing future scenarios.

Participatory approaches provide a limited, but consensual environment, in which a community of people can explore ways to achieve societal transformations. The added value of modelling in such contexts, as García-Mira et al., 2017 and others have shown, is in highlighting gaps in knowledge or reasoning. Holtz et al., 2015 note that models co-constructed with stakeholders are useful when discussing forecasts and scenarios. The sixth challenge of McDowall and Geels, 2017 cautions that models used in this way should be treated carefully: are such models a scientific artefact, or dialogue facilitation tools? They warn modellers not to be over-confident.

Questions of system transformation also have a profoundly ethical dimension. Who gets to set the agenda? Do we, as modellers, merely try to represent how societies are functioning – or will societal functioning start to mirror our theories? Models are not innately neutral or innocent. In addition, researchers should have in mind that "food security" is a political term. Hence, how they shape the focus of their research can amount to a political statement. With these caveats in mind, participatory approaches to modelling transformations to a food secure world have some promise.

A further important issue relates to sustainability transitions in general (cf. Sustainable Development Goals). Food production has potentially conflicting implications for other sustainability dimensions through the use of land and other resources (Frank et al., 2017; Wolff et al., 2018). Achieving environmentally sustainable global food security requires transformations that entail an integrated vision of human-environment interactions (Hadjikakou et al. 2019). In this regard, the integration of micro-scale agro-ecological models in macro-scale production-focused models may be insightful.

The use of models that bring together macro-level models and micro-level processes with emergent patterns seems to be a prerequisite for investigating transformation in food systems, especially if transformative change involves bottom-up social processes rather than purely top-down policies. If so, models should endogenously represent behavioural change by consumers or producers, social network dynamics, institutions and institutional change. Integrating these into food system models requires additionally developing the modelling capability to address cross-scale influences in all directions (cf. Hammond and Dube, 2012).

4 Key Conceptual and Methodological Challenges and Promising Ways Forward in Food Security Modelling

Building on our review of the three core issues, we have identified a set of overarching conceptual and methodological achievements and challenges. In the following, we address five of them: (1) Interdisciplinary thematic scope; (2) Representation of agency by exploring the roles of new agent types in food systems; (3) Appropriate techniques for representing relationships and feedbacks across scales and organizational levels; (4) Integration of different modelling approaches; (5) Empirical foundation, data availability and model parameterization. A sixth issue, explicitly modelling transitions (including unexpected change), has been addressed in Section 3.3 above.

4.1 Interdisciplinary Thematic Scope

An important step in any modelling process is “Problem formulation”, the establishment of the study’s thematic scope. Like many contemporary social and environmental challenges, understanding food security requires a multi- and inter-disciplinary perspective that integrates social and natural sciences. To guide research into such complex phenomena, newly established theoretical frameworks combine existing approaches and provide conceptual tools. For example, the telecoupling framework (Liu et al., 2013, Liu et al., 2018a) combines concepts of teleconnections and globalization with tools from systems thinking to provide a structure around which human-environment questions can be refined, data collected and analysed, and models developed. However, regardless of the conceptual framework around which any interdisciplinary research is structured, the vital issue is to identify the processes that are relevant to the research question and its context. For food security, this means paying special attention to currently under-represented processes in existing research (Figure 1). The inclusion of case study experts and relevant stakeholders is vital to the development of better model representations in these areas. However, researchers should be wary of allowing the scope of processes considered to become too broad (to help avoid the production of so-called ‘integronster’ models, cf. Voinov and Shugart, 2013).

4.2 Representing Agency

With regard to an improved representation of agency, three different issues arise. First, model features such as heterogeneous types of actors, their interaction, and bounded rationality are rarely taken into account. Initial attempts with equilibrium approaches exist: models have been developed where heterogeneous types of actors are included (cf. Melnikov et al., 2017; Lundberg et al., 2015). However, these approaches fail to include more sophisticated types of interaction than those that occur through markets. Agent-based models are able to include heterogeneity of actors and their interactions either through continuous agent characteristics or through some form of grouping or typology (e.g. Valbuena et al., 2010, Rounsevell et al., 2012). In this way, ABMs can be focused on the forms and ranges of behaviour that are of most interest in a given application without introducing superfluous complexity. Representing human decision-making in this way can benefit from expertise gained in behavioural economics and computational sociology (DellaPosta et al., 2015; Schlüter et al., 2017; Schulze et al., 2017). But a number of challenges exist, ranging from inherent characteristics of socio-environmental systems as complex adaptive systems (cf. Davis et al., 2018) to the limited synthesis of empirical studies on temporal dynamics of decision processes. Second, new types of actors play an increasing role in food security, including transnational companies, large land-owners, and agribusinesses. Current food security models do not reflect these types of actors and the related power dynamics (cf. Section 2).

Third, by enabling agency over a larger set of decisions (such as production methods, consumption, crop choices, adaptation/technology uptake, and marketing decisions), the challenge of complex interrelations in food systems can be approached. For example, for a promising first attempt, see Rutten et al., 2018, who present a modelling concept that pushes the boundaries of what elements of food security are considered.

4.3 Relationships and Feedbacks

An advancement of the limited set of techniques for scaling and representing feedbacks is critical to improved food-system modelling. In particular, including the feedbacks between micro-production, macro-trade and micro-consumption (back and forth) would be a significant improvement over traditional equilibrium approaches. Different approaches have proved helpful for upscaling information from the micro to the macro level (Ewert et al., 2011). They can be structured depending on whether the model input or output data are modified, the model parameters are adjusted or the model structure is changed when applying a model at different scale (ibid.). An example for changing the model structure or type is statistical/meta-modelling (e.g., summary functions and machine learning); summary functions from models/dynamics at the micro scale can be used to characterize more complex interactions at higher scales (e.g., SIMPLE-G-US, see Table 1 below). However, in general, their meaningful generation requires sufficient knowledge of underlying processes and relationships. New machine learning tools such as Deep Learning hold promise to broaden the possibilities of meta- (surrogate) models towards representing the relevant essence of lower scale models with high dimensionality, highly non-linear input-output relationships and dynamics in models at the macro scale. Data can be generated as needed for the required accuracy of the trained meta-model, but their application in place of the original model (as 'doppelgänger', van der Hoog, 2019) may help to overcome computational challenges in the macro-scale model trying to capture lower scale complexity and feedbacks. Applications of such data-driven approaches in food system or land-use modelling are limited and mostly related to the use of boosting techniques that allow higher flexibility than traditional regression approaches (Levers et al., 2018). However, in water resource modelling there has been more development in this respect (Asher et al., 2015). The second type of approach is a classification of land use(r) types using local scale (gridded) data for the identification of land systems (so called archetypes, cf. Václavík et al., 2013; Malek and Verburg, 2017) that capture characteristics of the underlying socio-economic system as part of the land-use classification. Rather than simulating the outcomes of food systems in terms of the symptom (i.e., land cover) a land systems approach aims to understand the changes in socio-ecological systems itself, providing a promising avenue to better understand regime-shifts and transformation of these systems (Debonne et al., 2018; Malek et al., 2018).

A remaining methodological question related to the upscaling of information is which aggregation level at the local scale is necessary to ensure "signals" significant enough to model macro-micro feedbacks. Novel approaches that allow flexibly adjusting model resolutions depending on modelling objectives and data availability are needed. Such approaches would support re-usable model structures that include important features such as micro representations, feedbacks, and the incorporation of dynamics.

4.4 Integration of Modelling Approaches

Currently, few modelling approaches are available that fully integrate feedbacks up from micro to macro levels. A way to bridge this gap is the comparison and integration of different modelling approaches for a specific research question. In this section, we discuss the potential for incorporating such feedbacks as well as integrating ABM and equilibrium approaches. Table 1 contains further examples that show promising ways forward for integrating different model approaches across scales. The table contains information on the availability of model code and input data, to allow researchers from external groups to reproduce and build upon existing results. Reproducibility and transparency is key to good scientific practice, and in the case of modelling studies implies the need for source code and data to be freely available.

Alternative modelling approaches come with different sets of intrinsic strengths and weaknesses (see 2.1 describing model types), making them more or less suitable for addressing different research questions. For example, economic equilibrium models, such as CGE (computable general equilibrium) and PE (partial equilibrium) models, are well suited to studying marginal changes across and between sectors of the broader economy. However, the assumptions contained within them imply that when existing trends change and the previous associated relationships no longer hold, they may be inappropriate. This includes capturing path dependence and non-linearity. Models that represent micro-scale processes (e.g. ABMs) may, if specified correctly, be able to capture these behaviours, render equilibrium behaviour transient, and replace optimization with other behavioural assumptions where appropriate. In particular, the impact of time lags can be studied through ABMs, including general characteristics of cobweb models (see Lindgren et al., 2015 for a stylized example of agricultural land use including trade and transportation). Additionally, a greater degree of heterogeneity of individual behaviours and spatial aspects can potentially be included in micro-simulations and ABMs than in typical economic equilibrium approaches. However, the challenges of specifying such models tend to create practical limits to the extent of the system represented. The complexity and degrees of freedom introduced can create challenges in calibrating and validating models, including ABMs. CGE/PE models' capacity to closely reproduce current behaviours and their focus on representation of large-scale aggregated interaction makes them particularly suitable for some questions, e.g. policy analyses. This leads to a desire to integrate modelling approaches to exploit the advantages of both (Rounsevell et al., 2014), for example, to use a CGE model to represent the whole economy, and an ABM to represent a sector in more detail including greater spatial detail and agent heterogeneity. While the use of CGE outputs as inputs or boundary conditions for detailed models, e.g. of a specific sector, is increasingly being practised, a two-way integration between these model types is far less common. The study of Niamir and Filatova, 2015 appears to be the only one that seeks to embed a sectoral ABM (in this case of the energy sector) within a CGE.

A more fundamental concern regarding using only CGE models in the context of food security is the assumption of equilibrium that is central to the framework. Although equilibrium is the core of most economic theories and frameworks, real economic systems are usually not in equilibrium as drivers continuously change. An equilibrium model represents the "target", a stable state that the economic system would move to if the environment did not change. The process of moving to an equilibrium and its speed are not captured in a comparative static equilibrium model and would instead require disequilibrium models, which have received varying attention in the literature over time (e.g. Kaldor, 1972; Martinás, 2007; Arthur, 2010; Frei and dos Reis, 2011). The analysis of food and nutrition security could make good use of modelling approaches beyond the equilibrium concept to capture processes with irreversibility, collapse or more generally, regime shifts. For example, a prolonged period of food shortage with malnutrition of infants and children at critical development stages, mass emigration, the slaughter of labour animals for food, the absence of schooling in favour of labour to secure food and water, the over-extraction of natural resources, and hunger-related death are irreversible to different degrees. Once these occur, the system is unlikely to go back to the previous equilibrium even if food becomes more abundant later. Consequently, other modelling approaches like ABM, or more generally those with a recursive dynamic structure, should be able to represent the path dependency created by shocks to the food system with irreversible consequences.

Table 1 displays information on several recent modelling efforts that integrate two or more scales and use innovative approaches to bridge them.

Table 1: Promising approaches to the integration of models by bridging scales

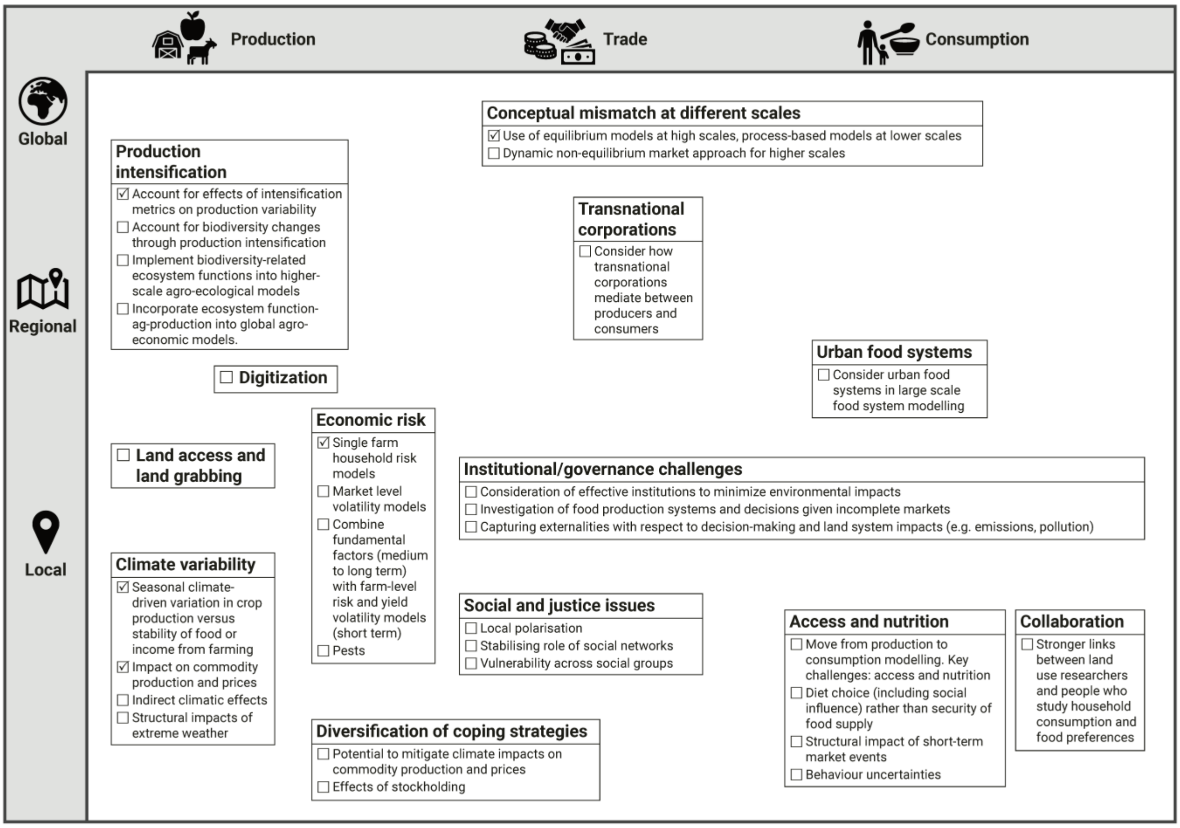
Reference /Model name	**Research question**	**Types of models coupled**	**Integrated scales**	**Innovative methodological elements**	**New insights gained**	**Availability of code and data, Information on reproducibility**
CAPRI/GTAP (Pelikan et al., 2015)	How Green are EU Agricultural Set Asides?	Computable general equilibrium model and partial equilibrium model (CGE and PE)	NUTS-2 regions, EU region and global markets	Theoretically consistent summary function, including a lever for set aside stringency	The set aside policy improves environmental status in high-yielding regions of the EU. However, output price increases lead to intensification in the more marginal areas of the EU. The decrease in arable land in the EU is partially offset by an increase of crop land, as well as increased fertilizer applications, in other regions of the globe.	All GTAP models and CAPRI are open source and freely downloadable. Most current GTAP data base must be purchased by non-contributors.
SIMPLE-G-US (Liu et al., 2018b)	What are the consequences of alternative measures aimed at reducing nitrate (N) leaching?	5 arc minute grid cell resolution of cropland within the US, nested within a 16 region, global PE model	Grid cells, national and global scales	Fitting summary functions to fine-scale, simulated data from Agro-IBIS on yield and leaching response to increased N use	N leaching fees sharply reduce output and raise corn prices; wetland restoration is the least disruptive method of mitigation.	Open source and also running on the NSF-funded GeoHub: https://mygeohub.org/tools/simpleus
CAPRI (Britz, 2008)	How do EU agricultural policies affect global markets? How do trade policies affection regional production?	Regional (NUTS2) agricultural programming models interacting with global multi-commodity market model	NUTS2, national and EU region	Iterative solving of regional production quantities and price reactions until convergence	It is possible to integrate technological detail at disaggregated farm level with global market feedbacks.	CAPRI model is open source (a general version can be downloaded from https://www.capri-model.org/dokuwiki/doku.php?id=capri:get-capri)
Diffenbaugh et al., 2012	Will market volatility increase in the face of climate change?	Gridded modelling of production, combined with an equilibrium model determining market outcomes	Grid cell, national and global scales	Use of statistical yield function to generate national yield volatility which feeds into economic model	Climate change will exacerbate future price volatility – particularly in the presence of biofuel mandates.	GTAP model is freely available. Crop response to climate is taken directly from Schlenker and Roberts
GTAP-POV (Hertel et al., 2009)	What is the impact of WTO reforms on poverty?	GTAP model of global trade and production interacting with micro-models of seven household	Global, national and household scales	Incorporates detailed survey data on the distribution of households around the poverty line and their earnings sources	The reform elements *left out* of the Doha Development Agenda (tariff cuts) played a more important role in reducing poverty than the elements *included* (cuts to output and export subsidies).	Open source, fully documented and free download from GTAP web site: https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3731

Reference /Model name	Research question	Types of models coupled	Integrated scales	Innovative methodological elements	New insights gained	Availability of code and data, Information on reproducibility
		strata, differentiated by source of earnings				
PLUMv2 / LPJ-GUESS (Alexander et al., 2018)	How resilient is the food system to global shocks, such as extreme weather events and geo-political changes?	Dynamic vegetation model (LPJ-GUESS) with global food system model (PLUMv2)	Crop yield potentials and land use decisions on 0.5° grid, national level import and exports and global agricultural commodity markets	Explicit representation of land use intensification versus expansion of agricultural areas, using spatially specific yield potentials from a process model of crop growth. Non-equilibrium market representation	Adaptation in the global agriculture and food system has capacity to diminish the negative impacts and gain greater benefits from positive outcomes of climate change. Agricultural expansion and intensification may be lower than found in previous studies where spatial details and processes consideration were more constrained.	PLUMv2 source is available from https://bitbucket.org/alexanpe/plumv2/src/default/ and LPJ-GUESS from http://iis4.nateko.lu.se/lpj-guess/download.html
Stürck et al. 2018 Lotze-Campen et al. 2018	1) Which affect has an increase in nature protection areas in the EU on different land-based sectors in and outside of Europe? 2) How does future land change trajectories look like across Europe?	Coupling land use models for agriculture, forestry, and urban areas in Europe, in connection with other world regions (CGE, PE, spatial explicit land use allocation models)	Global, EU, regional, local scale (until resolution of 1 km^2)	A whole modelling chain coupling seven models representing different land-based sectors and different scales in a spatial explicit way	Increase in nature protection areas has different implications in different parts of Europe. In addition agricultural production is shifted from more productive land in Europe to less productive land elsewhere.	MAgPIE model is open source (http://dx.doi.org/10.5194/gmd-12-1299-2019) for code availability of REMIND see https://www.pik-potsdam.de/research/transformation-pathways/models/remind Dyna-CLUE spatial land use model is open-source and available at www.environmentalgeography.nl; for CAPRI see other example
Zimmermann et al. 2017	What is the impact of climate change on European crop yields, land use and environment taking into account crop management adaptations?	Linking a crop modelling framework with a market model and an environmental impact model	NUTS2, country	Detailed specification of crop management adaptation and corresponding indirect yield changes in the context of an economic equilibrium model	Crop sowing dates and thermal time requirements affect crop yields, land use, production and the environment. However, effects of management assumptions were most pronounced for yields and less for economic and environmental variables	CAPRI model is open source (a general version can be downloaded from https://www.capri-model.org/dokuwiki/doku.php?id=capri:get-capri) The SIMPLACE crop modelling framework is also open source and available for download at: https://www.simplace.net/index.php
SEAMLESS-IF (System for Environmental	Two studies: 2. What is the effect of trade liberalization on consumers,	Integration of a cropping system modelling	Field, Farm, Region, Country, EU	Use of different types of scaling methods for manipulation of data (e.g.	Study 1. Elimination of the export subsidies and reduction in import tariffs resulted in a	CAPRI model is open source (a general version can be downloaded from https://www.capri-

Reference /Model name	Research question	Types of models coupled	Integrated scales	Innovative methodological elements	New insights gained	Availability of code and data, Information on reproducibility
and Agricultural Modelling-Integrated Framework) (Ewert et al. 2011)	farm income, employment and environment? 2. What is the impact of the European Nitrates Directive at the field, farm and regional level?	framework with a farming system model and a market model		extrapolation and aggregation) and manipulation of models (incl. statistical response functions, nested models)	price decline of agricultural commodities and in lower agricultural income Study 2. At field level: Improved nitrogen management leads to similar/lower nitrogen leaching; at farm level: different responses of arable farm types; at regional level: slight decrease of nitrate leaching and a high increase of water and labour use	model.org/dokuwiki/doku.php?id=capri:get-capri) Other models involved further developed by different consortia
MAGNET-GENuS	What are the trade-offs from plausible future food systems change on national food security and nutrient availability?	MAGNET model of global trade and production, linked to GENuS model for national nutrient availability	Global, national and household scales; food and nutrients	Explicit modelling of food and nutrient availability and affordability, to mimic food and nutrition security outcomes for representative consumer households	Downscaling of shared socioeconomic pathways (SSPs) to national level for Nigeria reveals implausible implicit assumptions on caloric outcomes. Structural transformation of food markets presents trade-offs between food security and affordable options for healthier diets.	Documentation in Smeets-Kristkova et al. (2019). The MAGNET model is licensed. GENuS is open access model (Smith et al. 2016)
MAGNET-Grid	What are plausible future changes in food consumption and food availability across metropolitan areas around the world?	MAGNET model of global trade and production, linked to Metropolitan Global-Detector for knowledge-based spatial analysis	Global, national, and household scales, linked with algorithm for cropping decisions at scale of 2.5x2.5 km grid cells	Projections for food demand at grid level, informed by demographic and economic drivers. Linking demand to land use and production decisions for crops at level of grid. Outputs of these models are downscaled to geographic maps for rural and metropolitan areas.	The application of the approach mimics the governance of the rural-urban linkages in the food system of the Ghana and the Accra metropolitan area. They provide a platform for integrating expert knowledge through stakeholder participation with evidence and modelling results.	Documented in Dijkshoorn-Dekker et al. (2019). The MAGNET model is licensed. Global Detector is R software, with restricted access.
TeleABM Dou et al. 2019, Dou (In Press)	Reciprocal land use change in China and Brazil. For example, 'if the Brazilian soybean region experiences a severe drought, what impact will this have on land use in China?'	Agent-based models of two landscapes are coupled by agent-based representation of national-level actors	Farm, municipality and national	Coupling two agent-based models reciprocally such that outputs from each model become boundary conditions for the other in each time step	Dynamics of international trade under "high-tariff" scenarios have profound local land-use impacts for parties in both producing and consuming regions	Source code available online via OpenABM at https://www.comses.net/

Reference /Model name	**Research question**	**Types of models coupled**	**Integrated scales**	**Innovative methodological elements**	**New insights gained**	**Availability of code and data, Information on reproducibility**
FLUTE Millington et al. 2017, Warner et al. 2013	How do events in one country (e.g., droughts, policy change) produce change land use in other countries?	Agent-based model (CRAFTY) coupled to a system dynamics model (BioLUC) of international trade and land use	Local (2500 ha), global (multiple countries)	Coupling ABM and SD models to reciprocally provide inputs and output during each timestep	Short-lived climate extremes and one-off policies have more significant effects on land use and trade dynamics than 'mean' climate change or gradual policy change	The CRAFTY model is open source and freely available online: https://landchange.imk-ifu.kit.edu/CRAFTY BioLUC is implemented in STELLA with source code online: https://github.com/StevenPeterson/CRAFTY-BioLuc Code to couple CRAFTY and BioLUC is available at: https://github.com/jamesdamillington/FLUTE_Maestro. Input data from Millington (2019)
CRAFTY SIRIOS Holzhauer et al. 2019	What are the most important aspects of institutional intervention (e.g. subsidy rate triggering threshold) for land use change	Single agent-based model representing local land managers interacting with institutional agents at two spatial scales	Local, regional, global (abstract)	Reciprocal interactions (influence and response) between institutions and land managers	Non-linear effects can change as land use changes, suggesting that the effects of climate change may require novel and responsive institutional action	The CRAFTY model is open source and available online: https://landchange.imk-ifu.kit.edu/CRAFTY

Apart from the challenge of bridging scales within one domain, addressing food security related research questions (cf. Figure 1) requires an integration of models representing different relevant environmental and socioeconomic processes across domains (cf. Robinson et al., 2018 who propose a conceptual framework for coupling models of human and natural systems). Depending on the research question, these may include, for example, hydrological processes or the impact of land use on biodiversity, consumer diet choice, and informal social networks. In doing so, dynamic coupling is also a prerequisite to investigate trade-offs in time (for instance between food security and biodiversity).



4.5 Empirical Foundation

Sound models require reliable data for adequate parameterization. The acquisition and use of suitable empirical data and parameters comes with several challenges. Aggregated data at a national level cannot capture the heterogeneity of food producers and consumers. Subnational units of analysis are necessary and will often lead to more nuanced findings (cf. Samberg et al., 2016). While it is crucial to capture relevant micro-scale mechanisms to reproduce and understand emergent patterns observed at the macro scale, it is difficult to obtain sufficient data in terms of both quantity and degree of detail. Meaningful comparative analysis, moreover, requires proper data and metrics that work and are consistent across scales and for all regions under consideration. Coupled process-based models also depend on the availability of biophysical and social data for different points in time. Ongoing initiatives such as the Long-Term Socio-Ecological Research (LTSER) observatories are an important step forward to provide coordinated data infrastructure and knowledge platforms (cf. Bourgeron et al., 2018; Dick et al., 2018). Generating such data, at global scale with adequate spatial resolution, is a costly and time-consuming endeavour. Existing collections of data (such as FAOstat and yield gap data) often have inadequate spatial resolution for disaggregated food security analysis; even reliable data sets may not be well documented or readily accessible (Hertel and Villoria, 2012). The FAIR principles (Wilkinson et al., 2016) provide guidelines for improved data management in the future. Finally, it is noted that access to and use of individual agent data is often restricted to avoid the identification of specific households, firms and individuals. Some techniques exist, such as random variations of geolocations, that still preserve most of the relevant spatial patterns in the data and its corresponding use in modelling without revealing identities (see Burgert et al., 2013, for an example). An alternative is a virtual data enclave allowing analysts to process the original data in models without possibilities to download and read (Richardson et al., 2015). Further development and implementation of these techniques will support the sharing of individual data and enhance the replicability of research results.

5 Outlook: How can Modelling Make a Difference to Food Security?

The contemporary research landscape around food security modelling is fragmented and incoherent across sectors and scales. Limitations and gaps in current modelling concern missing dimensions or scales with mismatches between concepts (e.g., ABM versus equilibrium models). Nevertheless, modelling is indispensable for better understanding the complex realities associated with food security. Recent efforts highlight the enormous potential in this field to inform decision making. Therefore, increased efforts to integrate models at different scales have the potential to contribute to achieving future food security.

Modellers can try to circumvent some of the methodological challenges discussed here by using ‘smart scenarios’ – instead of further increasing the complexity of models. For example, they could cover aspects in more complex scenarios that reflect outcomes of other models, such as the spread of new technologies in space and time. Nonetheless, the methodological challenges around the micro-macro link will need to be addressed more directly and completely. Further integration of the different interacting dynamics represented by different model types is required to better account for both multi-level agency and cross-scale feedbacks within the food system. Food system models also need to address underlying issues of food security such as poverty and inequality on a more comprehensive basis. This work could inform broader societal debates, e.g. concerning trade-offs between food security and environmental impacts.

We deduce several promising next steps from our assessment, which will hopefully help funding agencies and stakeholders to systematically work towards better tools and better understanding of food security challenges and solutions. First, to holistically address questions related to food security, large projects need to be initiated that have the capacity to study the relevant aspects and dimensions in conjunction with integrative methodological approaches. For instance, future work might usefully focus on the nexus of economic modelling of markets and ABMs. Second, networks of researchers spanning different countries need to be built and sustained with the goal to exchange, combine, and synthesize knowledge and methods that can advance the state of the art of modelling approaches to food security at local, regional and global scales. Third, platforms for the exchange of data, the replication of model results, and the exchange of ideas need to be developed. The progress achieved in other fields regarding technical implementation (such as modelling standards, common ontologies, and interfaces between models and to data) should increasingly be applied to the domain of food security modelling. Two examples are GeoHub (https://mygeohub.org/) and COMSES-Net (https://www.comses.net/). Developed with NSF funding, the open-source GeoHub hosts data and models developed by collaborators from around the world. COMSES-Net - “Network for Computational Modeling in Social and Ecological Sciences” offers a digital repository that supports discovery and good practices for software citation, digital preservation, reproducibility, and reuse. Platforms and endeavours such as this offer the potential to foster a community of practice focused on interdisciplinary modelling of food security. By continuing to integrate researchers and the different model types available, modelling will be able to better provide the necessary understanding about multi-level agency and cross-scale feedbacks within the food system that is needed to ensure sustainable global food security.

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7 References

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