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Modelling Food Security: Bridging the Gap between the Micro and the Macro Scale

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Highlights

- Our overview of food security modelling covers multiple disciplines & scales
- We identify & examine three core issues: volatility, technology and transformation
- Different conceptual backgrounds hamper model coupling
- Sound model integration is key for actionable research on sustainable food security
- Methodological innovations account for multi-level agency and cross-scale feedbacks

1 **Abstract**

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

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

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

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

24 **1 Introduction**

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

35 The imperative for multiscale analysis of the food system can be aptly illustrated with the case of the
36 US Renewable Fuels Mandate. Early systems analysis by environmental and energy systems engineers
37 found that corn ethanol production in the US could reduce life cycle greenhouse gas emissions (Farrell
38 et al., 2006). This was based on detailed analysis of direct emissions associated with the growth of the
39 crops as well as those tied to transportation, processing and delivery of the product to consumers.
40 However, the absence of any link to market modelling of agriculture and land use change led to the
41 omission of the indirect impacts of diverting a substantial share of food production into the energy
42 markets. Once this component was brought to bear, this government programme was found to have
43 adverse impacts, both on the environment and on food security (Searchinger et al., 2008), that can be

1 related back to the market effects of this policy (Hertel and Tyner, 2013). If early analyses had been
2 based on a multiscale model, the programme might never have gained such overwhelming political
3 support.

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

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

27
28 In the exploration of possible development pathways and their associated consequences, macro-scale
29 impact assessment models are currently in widespread use. These models typically simulate global
30 scenarios and explore large-scale consequences of policy options (e.g. Riahi et al., 2017). The mismatch
31 of scales and approaches between macro-level modelling and locally-determined processes and
32 indicators makes it difficult to answer critical questions, including: How can we better account for food
33 security when analysing long-term trends occurring at large scales (like economic development,
34 population growth, and water scarcity)? How can we quantify the trade-offs between different
35 indicators when searching for a sustainable future (e.g. van Wijk, 2014)? How resilient is the food
36 system in delivering appropriate nutrition under a range of shocks, e.g. extreme weather or geo-
37 political instability (Tendall et al., 2015; Urruty et al., 2016)?

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

1 Models that address food security issues operating across multiple scales often work either through
2 local-level proxies when analysing large-scale processes (for example through single crop yield
3 response functions or a single farming systems representation for a given geographical zone, e.g.
4 Hasegawa et al., 2018), or using global drivers when analysing local processes (for example through
5 commodity prices or farm size development scenarios, e.g. Herrero et al., 2014). More recently,
6 analyses at global or regional level have made transdisciplinary progress in finding solutions that take
7 more account of people's local reality (e.g. Ermolieva et al., 2017; Antle et al., 2014). Examples exist in
8 which interactions between drivers of food security at different levels have been assessed (e.g. van
9 Ittersum et al., 2008; Laborde et al., 2016; Ruane et al., 2018). These models are a first step towards
10 the multi-scale representation of land use, environment, and food security, but they still lack a more
11 complete reconciliation of processes across scales to capture relevant feedbacks (see also van Wijk,
12 2014).

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

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

25 **2 Current State of the Art of Food Security Modelling: Achievements** 26 **and Gaps**

27 Research on food security modelling is composed of a fragmented literature and methodology,
28 characterized by individual efforts in disparate disciplines with relatively few interconnections.
29 Although many literature reviews are available on the different types of modelling that might be, or
30 have been, applied to examine agro-economic or food-related issues (e.g. van Tongeren et al., 2001;
31 Ciaian et al., 2013; Francois and Martin, 2013; Kelly et al., 2013; Millington et al., 2017; Huber et al.,
32 2018, some addressing food security: van Dijk and Meijerink, 2014; van Wijk, 2014; van Wijk et al.,
33 2014; Brown et al., 2017), a comprehensive, interdisciplinary, multi-scale overview of food security
34 modelling does not exist in the current body of literature. To address this gap, we begin by providing
35 a summary of the modelling approaches that have been applied to examine aspects of food security,
36 before reporting on achievements to date and the outstanding challenges.

37 Food security, as defined by FAO, 1996, consists of four key elements (cf. also FAO, 2014): physical
38 availability of food; economic and physical access to food; food utilization; and the stability of these
39 three dimensions over time. Of these, availability and access to food have been most thoroughly
40 described, with new approaches currently being developed to better address utilization and stability.
41 In the following, we do not directly use these four pillars, but instead emphasize three primary
42 components of food security reflected in contemporary models: food production, trade, and
43 consumption. The interplay of these components is key to the challenge of feeding future global
44 populations (Godfray et al., 2010). We also discuss the stability dimension of food security which

1 requires dynamic models with high temporal resolution of economic and biophysical aspects (such as
2 commodity market volatility or pest occurrence and diffusion). Utilization of food is generally poorly
3 represented in modelling approaches and thus not considered here.

4 **2.1 Modelling Approaches**

5 Numerous approaches exist that are relevant to modelling food production, trade and consumption.
6 Agricultural production is a key aspect of food security modelled in multiple ways, including bio-
7 economic models (typically describing land use through optimizing an objective function like profit,
8 e.g., Janssen and van Ittersum, 2007), process-based land use models (describing the development of
9 land use and interactions with other factors over time through functional relations, e.g. Brown et al.,
10 2013; Verburg et al., 2016), multi-agent models (focusing on interactions between land users and/or
11 farmers' heterogeneity, e.g. Bharwani et al., 2005; Matthews et al., 2007; Ding et al., 2015), transition-
12 rule-based approaches (representing the transition between different states of the land, e.g.
13 Bestelmeyer et al., 2017 for rangelands) and econometric/statistical models (empirically describing
14 relationships between drivers of all different sorts and consequential land use, e.g., Munroe et al.,
15 2002; Millington et al., 2007). Models from different disciplines (e.g. economics, agronomy) tend to
16 have a different representation of core concepts, data types and state variables in space and time. The
17 following types of models simulating food production have been the workhorses for ex-ante analysis
18 and priority setting for the deployment of technological interventions and for examining trade-offs
19 related to the use of natural resources: (a) Biophysical crop models (for an overview see Müller et al.,
20 2017b), (b) farm management models (e.g. FSSIM, Louhichi et al., 2010, IFM-CAP, Louhichi et al., 2018,
21 also see Janssen and van Ittersum, 2007 and van Wijk et al., 2014) and (c) static and dynamic economic
22 models (e.g. CAPRI, Fellmann et al., 2018; AgriPoliS, Happe et al., 2006). In the integrated modelling
23 framework SEAMLESS-IF, an effort was made to link these types of models across scales in Europe (van
24 Ittersum et al., 2008; Ewert et al., 2009).

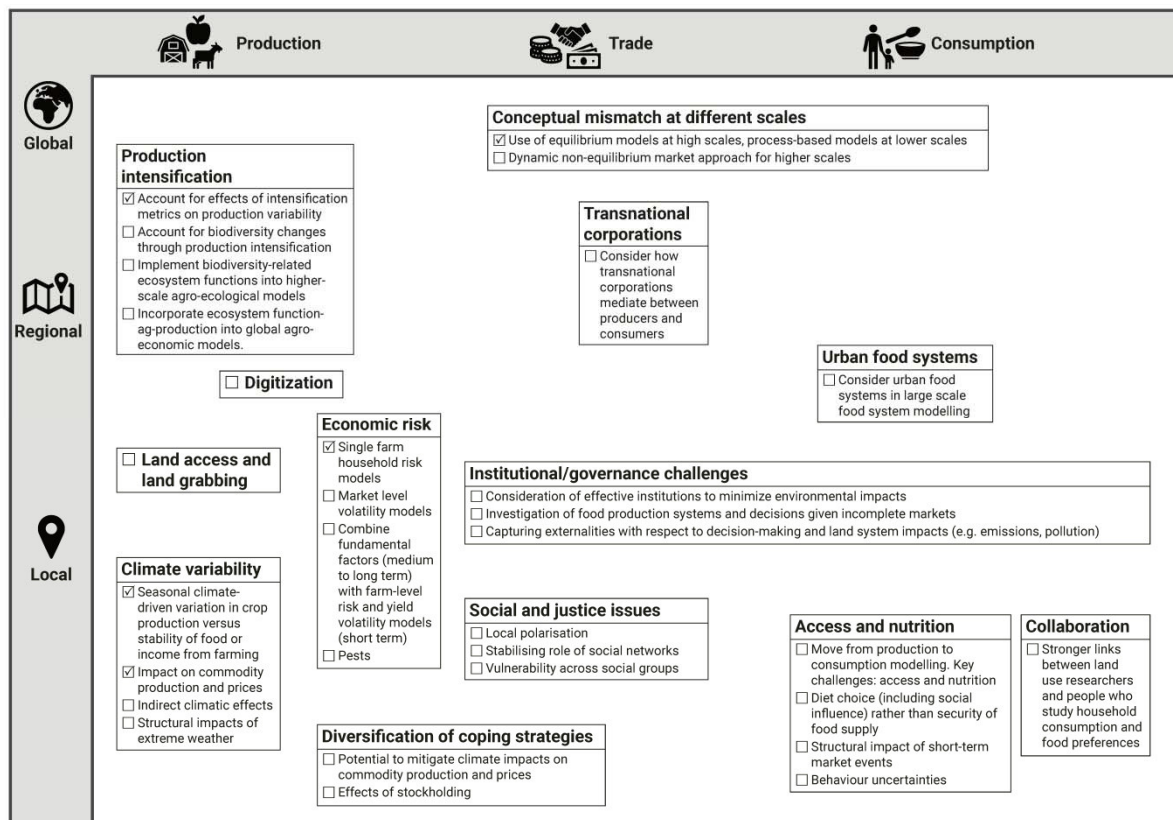
25 Moving from production to consumption requires a consideration of trade. Computable general and
26 partial equilibrium models have been used widely to examine how changes in policy or environmental
27 conditions could influence trade in agricultural and food commodities, both globally and regionally.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

39 On the consumption side, food allocation within and across households is critical to food security.
40 Agent-based approaches are increasingly used to assess food security of smallholders in developing
41 countries over time (e.g. Dobbie et al., 2018 which explicitly considers the four dimensions of food
42 security at the household and village level for a case study in Malawi). In a developing country context,
43 recent agent-based models (ABMs) analyse healthy food choices of consumers capturing interactions
44 between retail location, social networks and income (Tracy et al., 2018 pp. 82-83). Equilibrium models
45 are uniquely positioned to assess commodity and factor price impacts of perturbations to agricultural

1 supplies, technologies and policies (e.g. Hertel et al., 2007; Nelson et al., 2014a). These price outcomes
 2 are critical in determining the consequences for earnings, consumption, and thereby food security. By
 3 definition, these outcomes refer to a specific time period over which demands adjust to changes in
 4 supply and vice versa. Equilibrium models may be paired with micro-simulation models in order to
 5 determine household impacts of these types of shocks (e.g. Hertel and Winters, 2005; Cockburn, 2006;
 6 Cogneau and Robilliard, 2007).

7 2.2 Representing the Food Security Context in Models

8 To present achievements and challenges in food security modelling, we consider food production, trade, and consumption,
 9 across three spatial scales (



10

11 Figure 1). While we acknowledge that stability (temporal scale) is a critical dimension of food security
 12 (cf. Mehrabi et al., 2019; Renard and Tilman, 2019), we do not represent explicitly it in Figure 1, but
 13 assume that stability is an underpinning requirement in all depicted elements.

14 Climate-driven variability of crop yields has a large influence on the stability of food production at local
 15 to regional scales, constituting an important source of risk to subsistence farmers and low-income
 16 groups. Crop models are continuously developed to better capture seasonal and inter-annual yield
 17 variability as driven by weather and extreme events (Maiorano et al., 2017; Schauburger et al., 2017;
 18 Webber et al., 2018), but the applicability of crop models in integrated assessment studies is still
 19 considerably constrained (Ewert et al., 2015). Additionally, landscape-scale ecological properties and
 20 processes are most frequently neglected in food security modelling studies, including interactions
 21 across multiple trophic levels of food webs and trade-offs with biodiversity (van Noordwijk, 2002). A
 22 classic example for this is pollination. The presence of pollinating species is substantially promoted by
 23 heterogeneously structured landscapes (Klein et al., 2007; Kremen and M'gonigle, 2015; Kovács-
 24 Hostyánszki et al., 2017). A sufficient abundance of animal pollinators is critical for many crops that

1 provide vital micro-nutrients to humans (Eilers et al., 2011). An additional challenge lies in the currently
2 observable mismatch between models representing biophysical and socioeconomic processes (cf. also
3 Evans et al., 2013; Verburg et al., 2019).

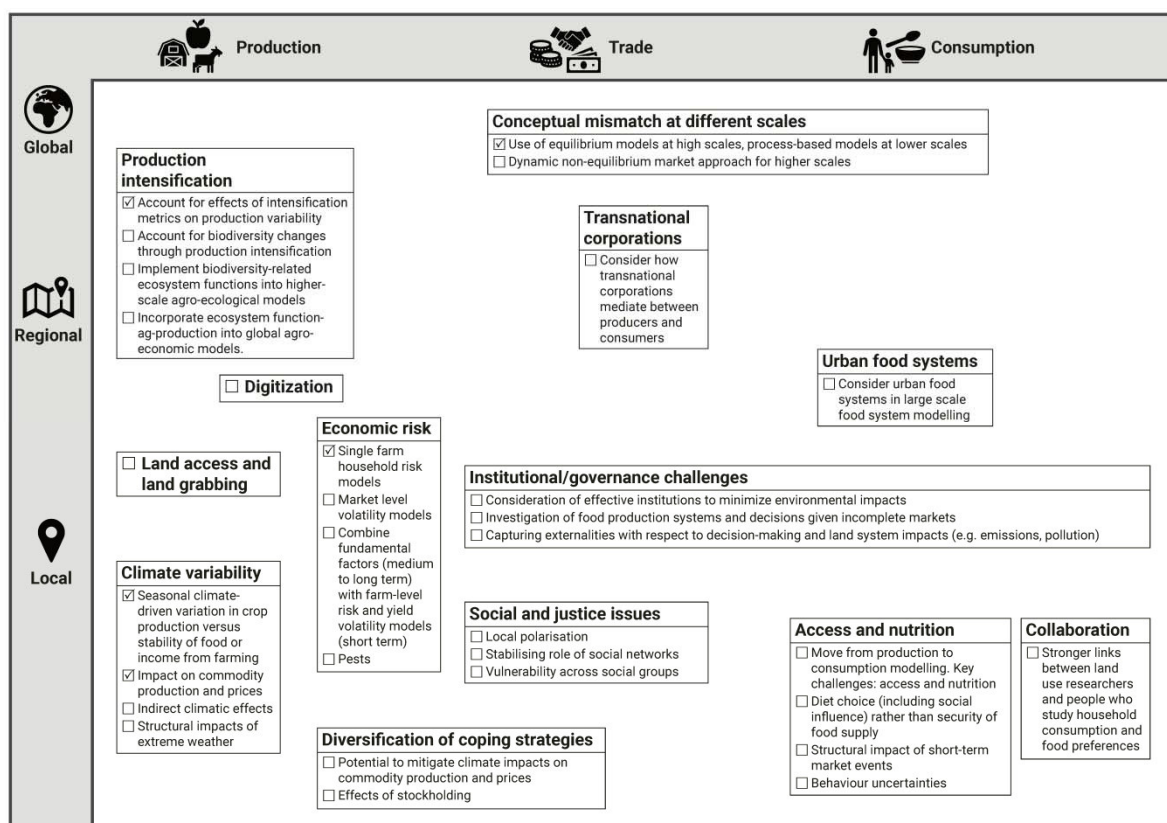
4 Climate variability also affects farmers' income. While many agricultural sector and market models can
5 consider impacts of climatic change on commodity prices (Nelson et al., 2014a; Nelson et al., 2014b;
6 Balint et al., 2017; Hasegawa et al., 2018; van Meijl et al., 2018), they generally do not consider short-
7 term variability from extreme events (with notable exceptions, cf. Schewe et al., 2017). They are also
8 generally unable to capture the economic impacts of such shocks, together with other abrupt social
9 and economic events, for example in limiting investments in agricultural technologies (Kalkuhl et al.,
10 2016; Cottrell et al., 2019). Similarly, many indirect effects, including migration, changes in land tenure,
11 strategies to cope with income shortfalls, and speculation on food prices, are also neglected.

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

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

40 While consumption closely relates to production activities and incomes for many smallholder farmers,
41 we consider it separately here, with a focus on access and nutrition, affected by heterogeneous
42 behavioural dynamics. Both developing and developed countries' specific risks of malnourishment are
43 under-represented in food security models, with limited consideration of nutrient deficiency or obesity
44 (for an exception, see Springmann et al., 2016) or differing vulnerability to price shocks of urban

1 consumers and rural producers. However, their representation will require collaboration with
 2 empirical experts who study household consumption and food preferences, as well as sources of
 3 household income (Ahmed et al., 2009). Beyond individual consumption, which is largely governed by
 4 individual resources and behaviours as influenced by social norms, transnational corporations have
 5 recently emerged as key entities leading to increased commercialization and concentration in global
 6 food chains (Gibbon and Ponte, 2005), with few exceptions (Sitko et al., 2018). Economic models rarely
 7 represent these corporations' role in directing market activity although they take over a crucial part of
 8 agency in real markets. Likewise, urban food systems have been given limited attention in terms of
 9 modelling (cf. Bodirsky et al., 2015 as an exception, where urbanization is discussed as a driver for
 10 modelling diets). Finally, food security challenges are also institutional: topics such as health,
 11 environmental protection, governance, and externalities can hardly be handled properly by models
 12 based solely on market calculations, even more since they vary in time, space, and across societies (for
 13 an exception, see Wang et al., 2016). In this respect, it is often the capabilities of current models that
 14 drive modelling exercises, rather than requirements of the food security issue.



15
 16 **Figure 1: Aspects of food security modelling.** They are arranged by spatial scale (y axis) and three key components of food
 17 systems (x axis). The temporal dimension is not represented here. We omitted several aspects (e.g. health, cultural
 18 dimensions, and non-spatial scales such as institutional scale, cf. Preston et al., 2015) in favour of clarity. Topics may span
 19 multiple levels. Most bullet points are about open questions, denoted by squares. Checked boxes, on the other hand,
 20 denote that these have been adequately addressed by modellers.

21 **3 In-depth Reflection and Analysis for Three Core Issues**

22 From our overview of achievements and gaps summarized in Figure 1, we identified three core issues
 23 for in-depth reflection and analysis. These issues – volatility, technology and transformation of the
 24 food system – embody distinct core components of food security and correspond, respectively, to
 25 short-, medium- and long-run adaptations to food insecurity. They serve to illustrate particular

1 challenges related to the micro-macro scale connection. For each core issue, we point out central
2 mechanisms to be included in models and present the current state of the art.

3 **3.1 Volatility: Uncertainty in Supply and Prices**

4 Uncertainties in commodity supply (e.g. due to extreme weather events or pests) can lead to
5 instabilities in food prices which are transmitted globally through markets. With little short-run
6 potential to adjust crop planting and technological choices, weather-induced yield variability can
7 dramatically impact prices, and hence the affordability of food (Wiggins and Keats, 2013). This problem
8 is particularly severe for urban residents and others who are net food buyers. To address these issues,
9 models need to incorporate processes such as storage and transportation (trade) to better
10 characterize the potential for mitigation of food price volatility (Wright, 2011; Burgess and Donaldson,
11 2010). Medium- to long-term adaptations by consumers, producers, investors, policymakers and
12 actors in the value chain to manage increased risk exposure might in turn affect short-term volatilities,
13 as intensification of crop production has an impact on its stability (Müller et al., 2018). Risk-coping
14 strategies such as formal and informal insurance and income diversification also need to be taken into
15 account.

16 Agricultural markets are vulnerable to uncertainties in supply, since production hinges on uncertain
17 weather conditions as well as environmental hazards such as pests. This is a complex modelling
18 challenge as weather effects can be highly localized, but the market outcomes represent the
19 aggregation of these local variations. Diffenbaugh et al., 2012 reproduced national historical yield
20 volatility in US maize production using fine-scale climate model output and crop production
21 information, linked through a non-linear yield response to temperature and precipitation estimated
22 by Schlenker and Roberts, 2009. Diffenbaugh et al., 2012 were able to replicate aggregate price
23 volatility using this approach. They show that climate-driven, supply-side uncertainty is likely to
24 increase under future climate due to more frequent exceedances of critical temperature thresholds.
25 The consequences for commodity markets in the face of price-inelastic demands are potentially
26 severe. Where storage is possible, price swings can be mitigated by agents taking advantage of those
27 swings to buy low, store the commodity, and sell when supplies are low and prices high (Roberts and
28 Tran, 2012). However, in the poorest countries of the world, pests, cash flow constraints and other
29 factors result in considerable storage losses, leading to lower storage rates (Kaminski and
30 Christiaensen, 2014). In much of Africa producers sell their harvest at low prices and end up buying
31 back grains at high prices during the 'lean season'. Introduction of low cost, improved storage
32 technologies can have a positive impact on household welfare in this context (Murdock and Baoua,
33 2014). It can also promote the adoption of new crop varieties which are high yielding, but more
34 vulnerable to pests (Ricker-Gilbert and Jones, 2015).

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

1 One important means of dealing with climate variability is insurance. Informal insurance through
2 extended families and social networks (Rockenbauch and Sakdapolrak, 2017) is widespread in many
3 developing countries, as is the sale of assets including livestock. However, these traditional methods
4 of insurance against unanticipated events are ill-suited to co-variate climate shocks, which tend to
5 affect the entire community/region (Dercon, 2005). In light of this, index insurance tied to regional
6 weather outcomes is a response which has been offered with great enthusiasm by some in the
7 development community. If it is publicly provided, it tends to have low transactions costs, more rapid
8 pay outs and it minimizes asymmetric information challenges (Giné et al., 2008; Cole and Xiong, 2017).
9 Yet the poor have historically been slow to adopt insurance, even where such markets exist (Kiviati,
10 2009). While there has been some progress on the adoption of micro-insurance across the developing
11 world (<http://worldmapofmicroinsurance.org/>), this is an area ripe for further exploration where
12 intended and unintended consequences need to be analysed (cf. Müller et al., 2017a for a review of
13 modelling and empirical studies of the impacts of agricultural insurance). Economic modelling studies
14 have been used on the farmer level (cf. Ricome et al., 2017) and on the financial market level (cf. Carter
15 et al., 2016) for studying the impact of insurance on land-use strategies or on technology adoption. It
16 would seem that agent-based models which focus on inter-household interactions and/or more
17 sophisticated representation of farmer decision making might be able to shed additional light on the
18 constraints and opportunities for more widespread use of index insurance (for first attempts, see
19 Müller et al., 2011 and John et al., 2019 on the impact of insurance on pastoral land use strategies and
20 possible side effects).

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

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

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

1 3.2 Technology: Dealing with Heterogeneous Innovation Spread

2 Technological innovation and diffusion across different domains of the food system (production,
3 marketing and trade, as well as consumption) is highly relevant to food security in the medium to long
4 term. Technology development including breeding and crop management has been the key driver of
5 productivity increases in the past and will be the most important driver for the future (Ewert et al.,
6 2005). In the face of increasing risk of supply shocks, agents in the food system would be expected to
7 adopt new technologies to adapt to new climatic conditions and mitigate the impact of extremes on
8 land use and productivity. Adoption rates vary according to decision-making characteristics such as risk
9 aversion, so that understanding the household level impacts requires models that capture the relevant
10 agent heterogeneity, at individual or typological level (Daloğlu et al., 2014; Brown et al., 2019).
11 Technology can also facilitate improvements in transport, marketing and storage. Technological
12 innovation is generally a process driven by private incentives to achieve higher productivity producing
13 more or better goods and services with fewer inputs (resources), and by public institutions aiming to
14 improve (agricultural) productivity to ensure long-term food security.

15 R&D spending creates “knowledge capital”, which drives productivity growth through technological
16 innovation. However, the capability to translate these investments into productivity gains varies widely
17 across the world. In a recent paper reviewing 44 empirical studies, Fuglie, 2018 finds that a 1% increase
18 in overall R&D capital leads to a 0.67% increase in agricultural output in developed countries but only
19 0.38% in developing countries (0.17% in Sub-Saharan Africa). Dietrich et al., 2014 propose a modelling
20 approach in which the costs of R&D for yield increases depend on the current intensity level. Spillovers
21 across regions and R&D categories (public and private) as well as accumulation and depreciation of
22 R&D capital over time creates complex spatio-temporal dynamics requiring appropriate modelling
23 tools to understand how public R&D spending influences agricultural productivity and thereby the
24 availability and accessibility dimensions of food security in the long run.

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

36 Global-scale research on the relationship between R&D and productivity shows that investment in
37 technology matters for food availability and access. However, it does not say much about the role of
38 the private sector and the impacts on heterogeneous actors. Digitization and automation may provide
39 technologies that fundamentally transform modern agricultural management without being “policy
40 induced”. The speed, level and spatial expansion of technology uptake by actors in the supply chain is
41 relevant for the macro-(market-)level and in turn feeds back to the adoption process (cf. Brown et al.,
42 2018a for empirical evidence for knowledge diffusion patterns in land use). Current integrated
43 assessment models that assume immediate uptake have been criticized as unrealistic (cf. Turner et al.,
44 2018). Closely related to the dynamics and spatial aspect of the diffusion process are questions like:
45 Who might gain access to these new technologies? Why might they choose to adopt them (or not)?

1 Will the technologies deliver their intended benefits ‘in the field’? And who are subsequent winners
2 and losers from these developments?

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

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

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

35 **3.3 Transformation: Moving to a Food Secure World?**

36 Radical and rapid transformative change of food production (and consumption) systems is possible.
37 Yao, 2000, for example, documents the economic reforms in China of Deng Xiaoping, starting in 1978,
38 which in six years increased grain production by a third and doubled real per capita incomes. Achieving
39 global food security, especially if we are to avoid increased environmental harm, will require
40 transformative change of a kind that may entail hitherto unimagined technology and social institutions.
41 Such transformative change poses a significant challenge not only for policy and society, but also for
42 modelling. Only recently have initial conceptual studies been published that investigate changing
43 institutions such as social norms or collective governance, mostly through agent-based or network
44 approaches (cf. Gräbner, 2016; Ghorbani et al., 2017; Scott et al., 2019).

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

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

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

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

38 This limitation of most current models is addressed by Holtz et al., 2015 in their review of the prospect
39 for modelling societal transitions. As a possible solution, they propose following Andersson et al.,
40 2014's suggestion that the required changes in ontology need to be embedded in the dynamics of the
41 model. By ontology, we refer to an explicit description of concepts and relationships in a domain of
42 interest (Gruber, 1993) that could be understood as the model's structure. Such changes are more
43 difficult to implement when modelling future, rather than reconstructing past, transformations.
44 Commenting on Holtz et al., 2015, McDowall and Geels, 2017, develop ten challenges. One of these
45 challenges (McDowall and Geels, 2017, p. 43) returns to the issue of structural change and offers an
46 alternative interpretation of Andersson et al., 2014's challenge of 'wicked systems' (both complex and

1 complicated) to modelling: that formal approaches are intrinsically limited, and narrative theories are
2 better suited.

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

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

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

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

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

37 **4 Key Conceptual and Methodological Challenges and Promising Ways** 38 **Forward in Food Security Modelling**

39 Building on our review of the three core issues, we have identified a set of overarching conceptual and
40 methodological achievements and challenges. In the following, we address five of them: (1)
41 Interdisciplinary thematic scope; (2) Representation of agency by exploring the roles of new agent
42 types in food systems; (3) Appropriate techniques for representing relationships and feedbacks across
43 scales and organizational levels; (4) Integration of different modelling approaches; (5) Empirical

1 foundation, data availability and model parameterization. A sixth issue, explicitly modelling transitions
2 (including unexpected change), has been addressed in Section 3.3 above.

3 **4.1 Interdisciplinary Thematic Scope**

4 An important step in any modelling process is “Problem formulation”, the establishment of the study’s
5 thematic scope. Like many contemporary social and environmental challenges, understanding food
6 security requires a multi- and inter-disciplinary perspective that integrates social and natural sciences.
7 To guide research into such complex phenomena, newly established theoretical frameworks combine
8 existing approaches and provide conceptual tools. For example, the telecoupling framework (Liu et al.,
9 2013, Liu et al., 2018a) combines concepts of teleconnections and globalization with tools from
10 systems thinking to provide a structure around which human-environment questions can be refined,
11 data collected and analysed, and models developed. However, regardless of the conceptual framework
12 around which any interdisciplinary research is structured, the vital issue is to identify the processes
13 that are relevant to the research question and its context. For food security, this means paying special
14 attention to currently under-represented processes in existing research (Figure 1). The inclusion of
15 case study experts and relevant stakeholders is vital to the development of better model
16 representations in these areas. However, researchers should be wary of allowing the scope of
17 processes considered to become too broad (to help avoid the production of so-called ‘integronster’
18 models, cf. Voinov and Shugart, 2013).

19 **4.2 Representing Agency**

20 With regard to an improved representation of agency, three different issues arise. First, model features
21 such as heterogeneous types of actors, their interaction, and bounded rationality are rarely taken into
22 account. Initial attempts with equilibrium approaches exist: models have been developed where
23 heterogeneous types of actors are included (cf. Melnikov et al., 2017; Lundberg et al., 2015). However,
24 these approaches fail to include more sophisticated types of interaction than those that occur through
25 markets. Agent-based models are able to include heterogeneity of actors and their interactions either
26 through continuous agent characteristics or through some form of grouping or typology (e.g. Valbuena
27 et al., 2010, Rounsevell et al., 2012). In this way, ABMs can be focused on the forms and ranges of
28 behaviour that are of most interest in a given application without introducing superfluous complexity.
29 Representing human decision-making in this way can benefit from expertise gained in behavioural
30 economics and computational sociology (DellaPosta et al., 2015; Schlüter et al., 2017; Schulze et al.,
31 2017). But a number of challenges exist, ranging from inherent characteristics of socio-environmental
32 systems as complex adaptive systems (cf. Davis et al., 2018) to the limited synthesis of empirical studies
33 on temporal dynamics of decision processes. Second, new types of actors play an increasing role in
34 food security, including transnational companies, large land-owners, and agribusinesses. Current food
35 security models do not reflect these types of actors and the related power dynamics (cf. Section 2).
36 Third, by enabling agency over a larger set of decisions (such as production methods, consumption,
37 crop choices, adaptation/technology uptake, and marketing decisions), the challenge of complex
38 interrelations in food systems can be approached. For example, for a promising first attempt, see
39 Rutten et al., 2018, who present a modelling concept that pushes the boundaries of what elements of
40 food security are considered.

1 **4.3 Relationships and Feedbacks**

2 An advancement of the limited set of techniques for scaling and representing feedbacks is critical to
3 improved food-system modelling. In particular, including the feedbacks between micro-production,
4 macro-trade and micro-consumption (back and forth) would be a significant improvement over
5 traditional equilibrium approaches. Different approaches have proved helpful for upscaling
6 information from the micro to the macro level (Ewert et al., 2011). They can be structured depending
7 on whether the model input or output data are modified, the model parameters are adjusted or the
8 model structure is changed when applying a model at different scale (ibid.). An example for changing
9 the model structure or type is statistical/meta-modelling (e.g., summary functions and machine
10 learning); summary functions from models/dynamics at the micro scale can be used to characterize
11 more complex interactions at higher scales (e.g., SIMPLE-G-US, see Table 1 below). However, in
12 general, their meaningful generation requires sufficient knowledge of underlying processes and
13 relationships. New machine learning tools such as Deep Learning hold promise to broaden the
14 possibilities of meta- (surrogate) models towards representing the relevant essence of lower scale
15 models with high dimensionality, highly non-linear input-output relationships and dynamics in models
16 at the macro scale. Data can be generated as needed for the required accuracy of the trained meta-
17 model, but their application in place of the original model (as ‘doppelgänger’, van der Hoog, 2019) may
18 help to overcome computational challenges in the macro-scale model trying to capture lower scale
19 complexity and feedbacks. Applications of such data-driven approaches in food system or land-use
20 modelling are limited and mostly related to the use of boosting techniques that allow higher flexibility
21 than traditional regression approaches (Levers et al., 2018). However, in water resource modelling
22 there has been more development in this respect (Asher et al., 2015). The second type of approach is
23 a classification of land use(r) types using local scale (gridded) data for the identification of land systems
24 (so called archetypes, cf. Václavík et al., 2013; Malek and Verburg, 2017) that capture characteristics
25 of the underlying socio-economic system as part of the land-use classification. Rather than simulating
26 the outcomes of food systems in terms of the symptom (i.e., land cover) a land systems approach aims
27 to understand the changes in socio-ecological systems itself, providing a promising avenue to better
28 understand regime-shifts and transformation of these systems (Debonne et al., 2018; Malek et al.,
29 2018).

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

36 **4.4 Integration of Modelling Approaches**

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

1 key to good scientific practice, and in the case of modelling studies implies the need for source code
2 and data to be freely available.

3 Alternative modelling approaches come with different sets of intrinsic strengths and weaknesses (see
4 2.1 describing model types), making them more or less suitable for addressing different research
5 questions. For example, economic equilibrium models, such as CGE (computable general equilibrium)
6 and PE (partial equilibrium) models, are well suited to studying marginal changes across and between
7 sectors of the broader economy. However, the assumptions contained within them imply that when
8 existing trends change and the previous associated relationships no longer hold, they may be
9 inappropriate. This includes capturing path dependence and non-linearity. Models that represent
10 micro-scale processes (e.g. ABMs) may, if specified correctly, be able to capture these behaviours,
11 render equilibrium behaviour transient, and replace optimization with other behavioural assumptions
12 where appropriate. In particular, the impact of time lags can be studied through ABMs, including
13 general characteristics of cobweb models (see Lindgren et al., 2015 for a stylized example of
14 agricultural land use including trade and transportation). Additionally, a greater degree of
15 heterogeneity of individual behaviours and spatial aspects can potentially be included in micro-
16 simulations and ABMs than in typical economic equilibrium approaches. However, the challenges of
17 specifying such models tend to create practical limits to the extent of the system represented. The
18 complexity and degrees of freedom introduced can create challenges in calibrating and validating
19 models, including ABMs. CGE/PE models' capacity to closely reproduce current behaviours and their
20 focus on representation of large-scale aggregated interaction makes them particularly suitable for
21 some questions, e.g. policy analyses. This leads to a desire to integrate modelling approaches to exploit
22 the advantages of both (Rounsevell et al., 2014), for example, to use a CGE model to represent the
23 whole economy, and an ABM to represent a sector in more detail including greater spatial detail and
24 agent heterogeneity. While the use of CGE outputs as inputs or boundary conditions for detailed
25 models, e.g. of a specific sector, is increasingly being practised, a two-way integration between these
26 model types is far less common. The study of Niamir and Filatova, 2015 appears to be the only one
27 that seeks to embed a sectoral ABM (in this case of the energy sector) within a CGE.

28 A more fundamental concern regarding using only CGE models in the context of food security is the
29 assumption of equilibrium that is central to the framework. Although equilibrium is the core of most
30 economic theories and frameworks, real economic systems are usually not in equilibrium as drivers
31 continuously change. An equilibrium model represents the "target", a stable state that the economic
32 system would move to if the environment did not change. The process of moving to an equilibrium
33 and its speed are not captured in a comparative static equilibrium model and would instead require
34 disequilibrium models, which have received varying attention in the literature over time (e.g. Kaldor,
35 1972; Martínás, 2007; Arthur, 2010; Frei and dos Reis, 2011). The analysis of food and nutrition security
36 could make good use of modelling approaches beyond the equilibrium concept to capture processes
37 with irreversibility, collapse or more generally, regime shifts. For example, a prolonged period of food
38 shortage with malnutrition of infants and children at critical development stages, mass emigration, the
39 slaughter of labour animals for food, the absence of schooling in favour of labour to secure food and
40 water, the over-extraction of natural resources, and hunger-related death are irreversible to different
41 degrees. Once these occur, the system is unlikely to go back to the previous equilibrium even if food
42 becomes more abundant later. Consequently, other modelling approaches like ABM, or more generally
43 those with a recursive dynamic structure, should be able to represent the path dependency created
44 by shocks to the food system with irreversible consequences.

45

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

2 **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 affect 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 <i>left out</i> of the Doha Development Agenda (tariff cuts) played a more important role in reducing poverty than the elements <i>included</i> (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

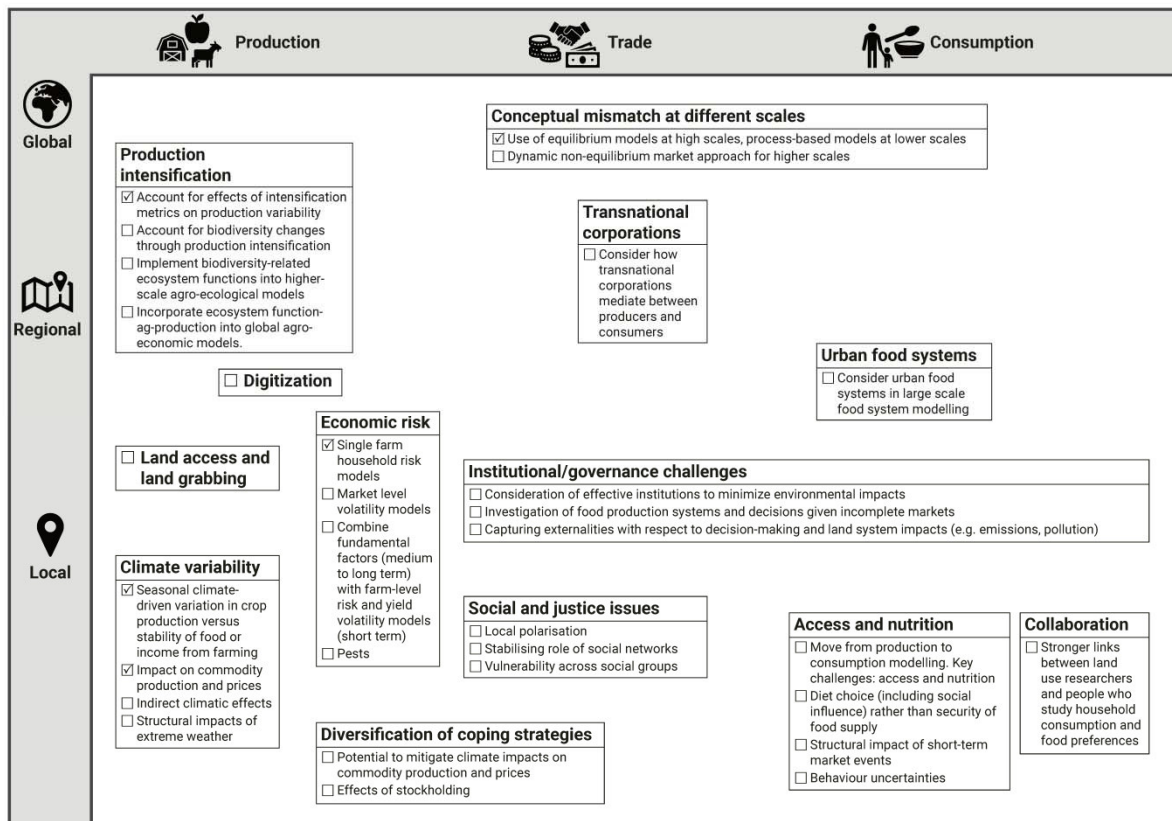
Reference /Model name	Research question	Types of models coupled	Integrated scales	Innovative methodological elements	New insights gained	Availability of code and data, Information on reproducibility
		strata, differentiated by source of earnings				
PLUMv2 / LPJ-GUESS (Alexander et al., 2018)	How resilient 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-paths/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 GENU 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. GENU 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 Diogo et al. (2020). 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

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1 Apart from the challenge of bridging scales within one domain, addressing food security related
 2 research questions (cf.



3
 4 Figure 1) requires an integration of models representing different relevant environmental and
 5 socioeconomic processes across domains (cf. Robinson et al., 2018 who propose a conceptual
 6 framework for coupling models of human and natural systems). Depending on the research question,
 7 these may include, for example, hydrological processes or the impact of land use on biodiversity,
 8 consumer diet choice, and informal social networks. In doing so, dynamic coupling is also a prerequisite
 9 to investigate trade-offs in time (for instance between food security and biodiversity).

10 4.5 Empirical Foundation

11 Sound models require reliable data for adequate parameterization. The acquisition and use of suitable
 12 empirical data and parameters comes with several challenges. Aggregated data at a national level
 13 cannot capture the heterogeneity of food producers and consumers. Subnational units of analysis are
 14 necessary and will often lead to more nuanced findings (cf. Samberg et al., 2016). While it is crucial to
 15 capture relevant micro-scale mechanisms to reproduce and understand emergent patterns observed
 16 at the macro scale, it is difficult to obtain sufficient data in terms of both quantity and degree of detail.
 17 Meaningful comparative analysis, moreover, requires proper data and metrics that work and are
 18 consistent across scales and for all regions under consideration. Coupled process-based models also
 19 depend on the availability of biophysical and social data for different points in time. Ongoing initiatives
 20 such as the Long-Term Socio-Ecological Research (LTSER) observatories are an important step forward
 21 to provide coordinated data infrastructure and knowledge platforms (cf. Bourgeron et al., 2018; Dick
 22 et al., 2018). Generating such data, at global scale with adequate spatial resolution, is a costly and
 23 time-consuming endeavour. Existing collections of data (such as FAOstat and yield gap data) often have
 24 inadequate spatial resolution for disaggregated food security analysis; even reliable data sets may not

1 be well documented or readily accessible (Hertel and Villoria, 2012). The FAIR principles (Wilkinson et
2 al., 2016) provide guidelines for improved data management in the future. Finally, it is noted that
3 access to and use of individual agent data is often restricted to avoid the identification of specific
4 households, firms and individuals. Some techniques exist, such as random variations of geolocations,
5 that still preserve most of the relevant spatial patterns in the data and its corresponding use in
6 modelling without revealing identities (see Burgert et al., 2013, for an example). An alternative is a
7 virtual data enclave allowing analysts to process the original data in models without possibilities to
8 download and read (Richardson et al., 2015). Further development and implementation of these
9 techniques will support the sharing of individual data and enhance the replicability of research results.

10 **5 Outlook: How can Modelling Make a Difference to Food Security?**

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

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

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

1 model types available, modelling will be able to better provide the necessary understanding about
2 multi-level agency and cross-scale feedbacks within the food system that is needed to ensure
3 sustainable global food security.

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