FACCE MACSUR

Challenges and research gaps in the area of integrated climate change risk assessment for European agriculture and food security

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Key messages

Climate change will affect human well-being and welfare through the impact on agricultural production of food, feed, and bioeconomy resources and as well as on the ecosystem and social services of rural agriculture. Associations among the many facets of agricultural production are non-linear and involve synergies and tradeoffs. In addition, these associations may vary across a heterogeneous, large spatial and political arena like Europe. For improved assessments of climate change impacts, existing modelling and assessment methodologies will have to be extended (or in specific cases new ones developed) to accommodate these heterogeneities and interactions.

Assessments at spatial scales of farm level or greater must include socio-economic aspects at time-scales greater than one year. At these scales, within-year and production-unit (plants, animals, plots) variation is dampened and variation in political settings, consumer attitudes and national economies, availability of resources, and value of products move to the fore.

FACCE MACSUR researchers identified needs for research to improve integrated assessments for information of policy, producers, consumers in five areas: (a) assessment criteria, (b) generalization of existing and new knowledge, (c) political and societal settings, (d) on-farm processes (generation of outputs from available resources, including their variation and disturbances), and (e) assessing implications of sub-optimal and technology-improved food production for global food security.

Priorities in addressing research gaps and challenges should follow the order of importance, which in itself would be a matter of defining goals and metrics of importance, e.g. the extent, impact and likelihood of occurrence. For improving assessments of climate change impacts on agriculture for achieving food security and other sustainable development goals across the European continent, the most important research gaps and challenges appear to be the agreement on goals with a wide range of stakeholders from policy, science, producers and society, better reflection of political and societal preferences in the modelling process, and the reflection of economic decisions in farm management within models. These and other challenges could be approached in phase 3 of MACSUR.

a) assessment criteria
  - goal priorities and goal compatibility determined jointly with stakeholders
  - agreement among all stakeholders on metrics for goal achievement
  - consideration of place- and time-dependency of goal priorities and metrics
  - assessment of food security with all its dimensions (availability, accessibility, affordability, nutritiousness, temporal variability) from the perspective of the consumer
  - definition of extreme events from a perspective of food security
  - combination of non-extreme events that coalesce to extreme events in terms of food security

b) generalization of existing and new knowledge
  - calculations of uncertainty hierarchies at farm level and upward the food value chain
  - transfer of knowledge in space, time, and scale: validation and training of existing models for new situations
  - linking of models taking more strongly into account the compatibility of model assumptions
  - definition of reference categories, especially farms crossed with other reference systems (e.g. climate, socio-economy)

c) political and societal settings
    - definition of details of consistent political, economic and societal scenarios for achieving SDGs that allow integration of models and their results
    - definition goal priorities for farm production and management from the perspectives of society and farm owner
    - accounting for changes in prices for resources for agricultural production
    - consumer attitudes towards production methods (e.g. organic, animal welfare, genetically modified) and product preferences (e.g. quality meat, vegetarian, regional)

d) on-farm processes (generation of outputs from available resources, including their variation and disturbances)
    - models reflecting to a greater extent and detail the many aspects of agriculture: farm economy, management, mass-balances for carbon, nitrogen, and phosphorus, ecological footprints, especially for mixed and livestock farms
    - replacing generic empirical model algorithms by process-based algorithms, especially addressing livestock production and farm management
    - improved collection and accessibility to on-farm primary data for model improvement in the areas of farm management and farm economy
    - better mechanistic representation of impacts of political settings and regulations (CAP, national agendas)
    - accounting more strongly for biological interactions (pests, diseases, symbioses, pollination, nutrient cycles)
    - improved reflection of variation by weather extremes, pests and diseases and their interactions with farm management and associated costs
    - extending the number of crop species, crop varieties, animal species and breeds in models
    - incorporation in models the adaptive management of variation in production and risk management (e.g. insurances, disease management, product diversification)
    - stronger consideration of farm-economic and societal effects of implementation of new technologies in farm management or the food-value chain (e.g. robot farming, on-demand farming, food printers)
    - stronger reflection of uncertainty, management options and risk management in the economic aspect of integrated farm models

e) assessing implications of sub-optimal and technology-improved food production for global food security
    - more explicit representation of areas of technological progress in integrated assessments and economic models
    - improved representation of management for assessing implications of sub-optimal production
    - more detailed feedbacks between physiological agricultural production and economic models

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1 Introduction

1.1 Agriculture, climate change, and models

Agriculture is a complex undertaking whereby environmental resources, capital, and labour are converted into food, other products, and services for direct or indirect use by humans. The changes in global climate to date and even more so those projected for the future threaten global food production and pose a severe challenge for food security. Models are suitable tools for exploring situations with a wide range of options and uncertain outcomes and are a good base for various forms of assessments. Given the current situation and selecting specific options for the future (called scenarios, what-if narratives, pathways, or counterfactuals), models can characterize the future state of variables based on current knowledge (empirical, experimental, and theoretical). Improved knowledge may lead to better models with improved projections of future food security, which in turn will help establishing a pathway for achieving appropriate adaptation and mitigation measures.

1.2 MACSUR within FACCE

Recognizing the need for research into adaptation and mitigation with respect to climate change, the Joint Programming Initiative FACCE launched a knowledge hub in 2012 to improve the European modelling capacity in the area of climate change and food security. The knowledge hub 'MACSUR' (Modelling European Agriculture with Climate Change for Food Security) currently comprises a network of 70 partner institutions in 18 mostly European countries. MACSUR members work across disciplines in the areas of crop production, livestock production, socio-economy, and adjacent topics.

The assignment by FACCE for the knowledge hub was that of creating a visible network to address uncertainties around the impacts of climate change on agriculture through the use of models. Important steps expected to achieve this goal were fostering interaction among the scientific disciplines, improving the modelling methodologies, developing of adaptation scenarios, and providing a climate change risk assessment that includes risks and opportunities emerging from adaptation pathways. Network activities are funded through national contributions to each partner organisation, plus additional in-kind resources by these institutions.

1.3 MACSUR Activities

MACSUR has started building an active research network since 2012 by bringing together scientists working in the areas of climate change impacts and agriculture and is now extending beyond the funded consortium of partners. For example, the crop modelling conference iCROPM2016 was attended by almost all leading international crop modelling groups. Fundamental organisational work has been carried out by collecting information about relevant models in use, listing their properties, finding data to use for evaluating model performance, agreeing on joint scenarios, looking for ways of transferring greater details of information among models, and using the interaction with stakeholders for improving the models and the interpretation of results. A great deal of work has been conducted to improve methodologies of modelling, especially within crop science. Additional work has been invested in training of junior and senior scientists, improving the applicability of model results, and disseminating the results to main stakeholder groups, i.e., policy makers, farm advisors, scientist.

1.4 MACSUR Results - overview

MACSUR has improved modelling of climate impacts on agriculture in several ways: physical, biological and management processes are reflected in greater detail in models, uncertainty of model results has been characterized through ensemble simulations, comparisons of simulations from different models based on identical data have improved the interpretation of model output, methods have been developed for identifying efficient granularity of input data for upscaling, other methods have been developed for summarizing data output for quicker assessments. Linkages among models have been improved for connecting grass production to livestock nutrition, weather and climate impacts to greenhouse gas emissions, environmental changes to livestock health and global cereal prices to regional farm income. Interactions with stakeholders in regional case studies have highlighted the producers' perspective of legal regulations that affect farm management and interfere with adaptation and mitigation options. Coordinated approaches to modelling and stakeholder interaction led to the identification of most suitable, regionally tailored adaptation pathways as well as their anticipated impacts on soil health.

1.5 Gap analysis: approach and focus on farm scale

The substantial improvements in modelling achieved during the first two MACSUR phases also identified research gaps where more effort is needed, what challenges must be overcome in the future and where current knowledge is insufficient. Gaps may be related to lack of knowledge, requiring better understanding of processes and collection of appropriate data, or may be related to logistical challenges, requiring investments in research methodology (high performance computing, stakeholder involvement, multi-disciplinarity, addressing competing goals).

One important goal of MACSUR is providing state-of-the-art risk assessments of climate change impacts on food security. Food security is one of the globally accepted sustainable development goals (SDGs, United Nations (UN), 2015). Policymakers expect that model results guide their decisions for reaching the SDGs. This requires on the one hand a broad spatial perspective and on the other hand knowledge of impacts at the smallest agricultural economic unit, the farm. Farms are also the unit where adaptation to climate change and mitigation of GHGs are jointly implemented. At farm level, adaptation and mitigation actions, farm economy, environmental and social effects must be compatible with each other and with sustainable development targets.

For identifying knowledge gaps and challenges at farm-scale in a structured way, it is useful to start from a simple concept of the interactions among drivers and settings, inputs and outputs of a farm. The concept illustrated in Fig. 1 will be used for addressing gaps in understanding the above-mentioned interactions and their consequences.

FARM PROCESSES (Fig. 1) use certain INPUTS (resources) in a given environment to produce a range of OUTPUTS (products and by-products, including side-effects) for a financial gain (INCOME). The SETTING, with the physical and social environment, its policies, consumer demands, research, technology and development, affects how a farm operates, the availability and quality of inputs, consumer preferences, farm economics, and the quality and quantity of outputs. It is represented by a hierarchical arrangement of the SDGs ("wedding cake"). VARIATION and DISTURBANCES may affect the setting, the input to farms, the way a farm operates, and hence the output and income of a farm.

Within this concept, knowledge gaps and challenges can be attributed to the setting and inputs by their quantity, quality and variability, the potential disturbances, and the processes at **farm-scale and sub-farm-scale** that affect the quality of projecting output variables and farm income. Finally, we can identify gaps in the modelling **methodology** itself.

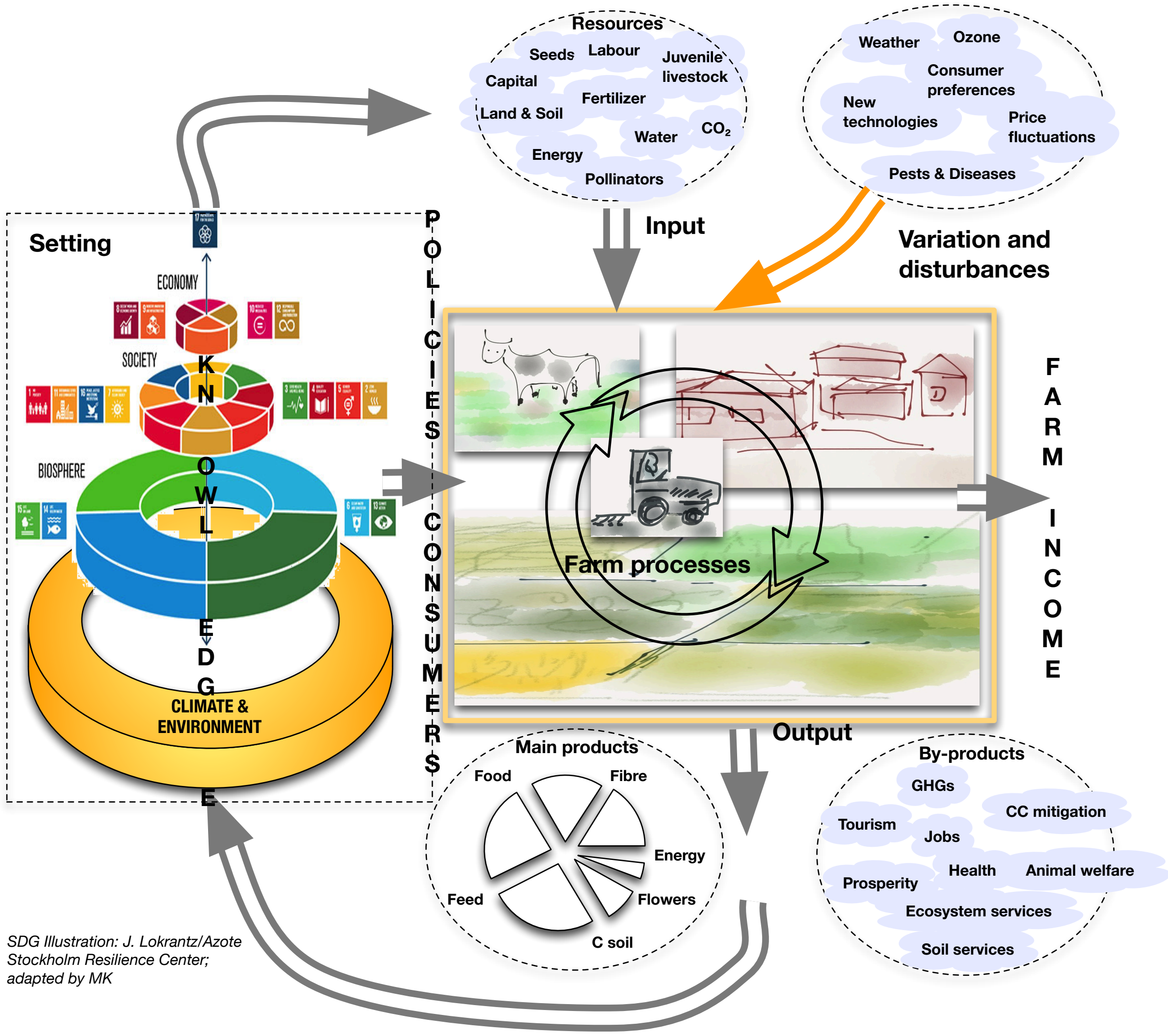

Fig. 1. Concept of relationship among inputs, outputs, settings and farm income for assessing gaps in agricultural research with climate change for food security.

2 Knowledge gaps and challenges in modelling agriculture with climate change at farm level

2.1 Goal priority and compatibility

Agriculture serves many purposes. When the intention of modelling is to determine ways for achieving several, mutually dependent goals, e.g. increasing the production of food, feed, and bio-economy resources while reducing GHG emissions and impacts on ecosystem services and providing a sustainable income for farmers, an optimal solution requires that competing goals are identified and ranked. This ranking must be situation-specific because agriculture is unique in every place: e.g., the same management practice will vary in its effects according to location. Ranking will also have to be scale-specific, because different goals and variabilities exist along the scales from farm to region to country to continent (Kouadio and Newlands, 2015). Rankings, therefore, need to be outcome-based and not action-based.

Rankings ought to be based on metrics that have been agreed on by a wide range of, if not all stakeholders. Bellocchi et al. (2015) provide an example for the involvement of stakeholders in rating model performance. Consensus needs to be reached on what ought to be measured and how. Families of metrics required include:

- **Efficiency and productivity metrics:** these include assessing yield per unit of input (where input could be water, energy, nutrient, pesticide, GHG impact, land), and addressing the question of how to assess yield (in terms of caloric, nutritional or economic value) and assessing impact per unit of agricultural product (output).
- **Field-level metrics:** metrics of soil carbon, structure, loss *via* erosion, impact of management on ground water, management of the marginal land and its value for promoting biodiversity or ecosystem services.
- **Landscape-level metrics:** for biodiversity (which species, which groups, which scales?); metrics for a range of ecosystem services including those supporting agriculture (pollination, pest control), water quality, and the cultural and amenity value; metrics that consider spatial teleconnections (water pumped for irrigation, transportation of goods, energy production)
- **Social and economic metrics** at farm and landscape level. These may include metrics assessing overall large-scale systems' performance (e.g. promoting system performance: contributing to a "mixed farming landscape" may help optimise at the landscape level in addition to affecting focal farm performance); contributing to food security (affordability, accessibility — see section 2.8) and other SDGs within the region or globally.

Additional metrics may be required to assess **resilience** (tendency to return to stable state).

How to develop appropriate metrics is a key research question (Godfray and Lawton, 2001). For example, how do you assess outcomes, at field, farm, or system level, for farm management on biodiversity, where changes in biodiversity are equally governed by landscape-scale processes and weather? To what extent, given measurement biases, can standardised techniques apply in every situation and every location given measurement biases? Beyond the field or farm scale, what is the most appropriate "large scale" to consider?

In addition, any meaningful utilisation of the metrics requires the addressing of a range of further research questions. For example, how should the multiple aspects of sustainability be weighted against each other? Are some absolutely more important (and if so which)? Are some more important at some times or places (or timescales and spatial scales)? Over what time period should outcomes be assessed? (E.g. in a 5-year period, there is scope for offsetting bad performance in one year against improved performance in other years.)

An area of considerable interest is the extent to which different aspects of environmental impact correlate positively or negatively, and how these **synergies** and **trade-offs** may vary with context. Where trade-offs exist, to what extent can they be softened by appropriate management or technological intervention?

All changes in management that result from trying to improve sustainability will involve some degree of opportunity cost. Doing one thing rules out doing others. Furthermore, the costs of change will, if left uncompensated, often fall disproportionately upon the farmer.

After all, the present mosaic of land uses in an agricultural area reflects to a considerable degree, the farmers' attempt to maximise long run profits within the constraints of the physical environment, the policy context and price and cost expectations. Existing data indicate clearly that profit is a major determinant of land use — so if changing land use in a more sustainable direction will, on average and in the short-term, lower profits, that land use change would be more unlikely to occur. This therefore requires identification of ways to account for so-called external benefits (e.g. compensate for profits foregone by payments for ecosystem services).

In short, we need research into (i) trade-offs and synergies and (ii) costs and benefits, (iii) context- and place-dependency of trade-offs and synergies. Only by bringing these together will we be able to formulate recommendations for sustainability which will generate real-world change. This of course necessitates the inclusion of economic cost-benefit analyses of sustainability initiatives as a key aspect of the metrics side (Gadanakis et al., 2015). This would allow us also to change the definition of efficiency to one where we look at the net benefits of changes. This would further allow us to calculate the compensation needed to induce change or the consequences of altering regulations.

Existing practical examples show that significant value increases in agriculture can be obtained when all potential services and their values are included in planning (Bateman et al., 2013).

2.2 Challenges in generalisation of existing knowledge

We know a lot already, but how far can we apply our knowledge? For example — a relationship has been shown between warmer climate and stronger economy in China across ten centuries (Tao and Zhang, 2013), but can this be extrapolated to the future and generalized to all climates, all countries, any levels of change? What levels of uncertainty accompany the results or projections? Many models can be used with a generic, default set of parameters. These parameters should be tuned to the specific situations where a model is applied. Lack of time or funding may prevent the collection of appropriate data for parameterizing a model, or the model may even be applied in contexts for which it has not been designed. In some cases, experience has shown that this works satisfactorily. E.g. the soil model Roth-C (Coleman and Jenkins, 1999), originally developed for C_{org} turnover in arable soil, has also been applied to grassland and forest soils. Multi-model comparisons on standard data sets (similar to round-robin tests for laboratories) can identify strengths and weaknesses of models and have been used in climatology, economy, crop production (Elliott et al., 2015) and grassland production (Sándor et al., 2016), and N emissions from soil (Zhang et al., 2015). What, however, are the further consequences and uncertainty in results of using different models along a modelling chain? This remains to be evaluated. Any modelling study should encompass a sensitivity or uncertainty analysis due to the variation in farm data, emissions factors, allocation approach and system boundaries used (Crosson et al., 2011). In addition, far more effort should be spent on defining where models do *not* apply, instead of the natural need to demonstrate what they *can* do. Alternatively, genetic algorithms, actor-based approaches or other adaptive modelling methods could be used to improve model plasticity, that is, the ability of models to change their behaviour with changing conditions.

Conceptually, the use of model ensembles for assessing uncertainty range helps understanding how the existing knowledge can be generalized (Wallach et al., 2016). That is, we know that model outputs are affected by several sources of uncertainty (e.g. from process modelling). To handle such uncertainty, applying a model ensemble is a good start. However, this might not be enough, as mechanistic models might provide unreliable results when applied for novel conditions, very different from those for which they were developed. Also, ensemble composition and size may influence ensemble results. Therefore, there is the need for a generalization of the procedures for comprehensively interpreting model results in all kind of modelling studies using ensembles (Ruiz-Ramos et al., 2017).

In practice, stakeholder and policy makers need probability estimates to assess the seriousness of a projected impact thus taking the more appropriate decision (Schneider, 2001). A realistic assessment of uncertainty is thus especially important when extracting practical recommendations are meant to be extracted from climate impact assessment modelling studies. This is especially true for rainfed cropping systems, for which even small discrepancies in precipitation projections can result in different impacts and therefore adaptation recommendations. On the other side, adaptation is difficult to generalize, as optimal combinations of genetic material and management can vary largely from one location to another even across short distances. Therefore, any attempt of generalization should be at the methodological level, as adaptation implementation is mainly local. Again, one approach for dealing with complex situations while accurately assessing the uncertainty range is the application of model ensembles, to create impact (Pirttioja et al., 2015) and adaptation response surfaces (Ruiz-Ramos et al., 2017), in combination with probabilistic climate projections. This methodology allows associating likelihoods to the projected impacts taking into account for uncertainties in both crop and livestock models on the one hand and climate models on the other hand, thus providing more useful information.

For applying knowledge and making recommendations, it is helpful if one can refer to categories of farms, so that modelling activities can focus on typical cases. Furthermore, classification of farming systems will ensure identification of relevant data and a standardised way of model comparisons. Linking models or their outputs to specific categories may facilitate incorporating small-scale processes into large-scale processes. The linking to a variety of farm categories provides an additional way for identifying the strengths and weaknesses of existing models. Making this information available to stakeholders and incorporating their needs, interests, and feedback into modelling approaches will likely increase the acceptability and applicability of the output (Özkan et al., 2016).

2.3 Knowledge gaps in defining the setting

The availability of consistent scenarios allows comparisons among different studies and reduces the unlimited number of potential future conditions to a manageable size. With the introduction of the Shared Socio Economic Pathways (SSPs), which have been developed by the different key climate research communities in order to be able to explore the long-term consequences of anthropogenic climate change and possible responses (O’Neill et al., 2014) an important step has been made towards consistent scenarios for the analysis of integrated climate change risk assessment for European agriculture and food security. But as SDGs (United Nations (UN), 2015) had not been finally defined by the time of the development, explicit integration of these goals into the SSPs is still lacking.

It is necessary to include economic development and all its dimensions into narratives of future worlds and this has already been started in the SSPs. For example, a world with strong inequality between countries, but also sustainable future are part of the scenarios set. But the concrete attribution of level and depth to which concrete SDG targets will be achieved by 2030 to the different SSPs is not yet implemented in the SSPs, making a comprehensive scenario analysis difficult. For the political/country level, in addition to farm/ regional-level metrics (section 2.1), we suggest to use the SDG indicators, accompanying the 169 targets (United Nations (UN), 2015), as a metric to define in a concrete way in which Pathway which target has been realized and to which degree. As the indicators provide concrete and measurable units, such an endeavour should be undertaken for each single target. For SDG1 (to end poverty in all of its forms, everywhere) for example, five scenarios could be defined, determining the number or people who will still live in extreme poverty by 2030.

The SDG framework shows that goals and hence policies are linked and must be considered together. For example, sustainable development goals with relevance to food security are 1: zero poverty, 2: zero hunger, 3: good health & wellbeing, 12: responsible consumption and production, 14: life below water, 15: life on land. One can even claim that all SDGs are directly or indirectly linked to food (Rockström and Sukhdev, 2016). The effects of programmes implemented (or planned) to achieve one SDG may have non-obvious side effects on the realisation of other SDGs, prominently exemplified in the multiple expectations on agriculture to provide resources for food, energy, bioeconomy and the ecosystem. Therefore, these connections must be made clearer in the future and should be laid out to policymakers.

Finally, 'food security' is still very much largely focused upon production of food, but for a complete picture of food security, research (and policymakers) should consider that consumers can become food insecure through far more than failures of production, e.g. through deficiencies in food distribution, storage, timing, pricing.

2.4 Knowledge gaps in characterizing input variables/data

The challenges regarding data and their characterisation can be described in four categories: data quality; data accessibility; terminology and measurements; and validation of empirical relationships (Özkan et al., 2016). New experimental studies and surveillance as well as collection of data from a variety of regions with different climate conditions are likely to improve data quality. There is a need to create links and improve communication between modellers and those who collect, process and store the required data. Where data accessibility is limited due to regulations and restrictions, an inventory of such rules and relevant official support will be needed. In addition, a collection of terms and measures used in modelling will facilitate the communication among different modelling groups. Finally, the underlying mechanisms in empirical relationships need to be assessed and improved (Özkan et al., 2016). Several programs and initiatives have been started to improve the situation (FAO, GODAN/IGAP, ODJAR, GlobalSoilMap.Net, GEOSS, ICOS) but connectivity and accessibility of databases still require a large international effort. Accessible, shared inventories of models, approaches and data, are a resource for stakeholders and stimulate new research (Kipling et al., 2016a). FACCE JPI and MACSUR are in a good position to act on these issues and engage a global community through their memberships in programmes like the Global Alliance on Climate Smart Agriculture.

2.5 Variation and disturbances

Variation and disturbances may affect positively or negatively, beneficially or harmfully the amount and quality of physical input (resources), environmental conditions (e.g. weather), policies (e.g. CAP), biological interactions (e.g. diseases, pollination), financial issues (e.g. fertilizer prices), and consumer preferences (e.g. diet). Variations may be slow and foreseeable or drastic and unexpected. It is not only necessary to identify the variation and disturbances but to assess their implications for farm management and quantify the impacts on outputs, on farm income, and SDGs.

Among the changes that are slow and fairly predictable for the next decades are global population growth, climate change (especially mean temperature), the growing need for animal feed stocks and change in seasonal timing in managing farms. Even though these issues can be projected well, they are often not included simultaneously in projections. Thus, several economic baselines ignore global population growth and climate change.

Issues that require more intensive research include the variation brought about by consumers (changes in their attitudes and behaviour), weather other than mean temp and rain, air pollution, and extreme events (in several aspects: climatic, social, economic).

2.5.1 Consumer attitudes and demands

Consumers, their attitudes and revealed behaviour (e.g. buying preferences), have a strong influence on what agricultural production is economically viable. Health issues, animal welfare, dietary needs and concerns, religious, ethical and political considerations can determine which products are grown. This applies not only to local consumers, but also to consumers elsewhere in the case of traded goods. The role of the consumer is also the lever of policy and business for pursuing their respective goals. For example, meat production is not only driven by the consumers’ intrinsic preferences, but farmers and agrifood businesses also influence consumers through advertisement and political lobbying, as well as via their business strategies. There is little exploration around this role played by the industry, and the importance it has for mitigation strategies. This could be assessed at different levels (EU or national) through modelling in order to estimate consequences for CO_2-emissions (Springmann et al., 2016) and the SDGs under different scenarios concerning consumer behaviour, for instance a change in diets due to taxation, or policies that change preferences.

Increased knowledge about the health benefits of food with low carbon footprint, as well as more knowledge about the climate impact of food, will most likely have a certain, although limited, impact on consumer preferences and dietary choices. Present knowledge levels, especially about climate impact, are very low (Bailey et al., 2014). If increased knowledge is coupled with a strong popular trend towards veganism and vegetarianism, the change may be substantial and highly noticeable (Marsh and Guardian readers, 2016). A lower fraction of animal-based food would not increase both human health and reduce GHG emissions. In economic terms, these health benefits might be comparable to the environmental benefits of avoided climate change (Springmann et al., 2016).

Requirements for animal-based products, advantages of animal-based products, as well as trade-offs of animal production with respect to environmental issues and consumers health (in function of occurrence of extreme events mentioned in 2.5.4) might delay or change a trend towards a diet based on less meat. Increased concern with animal welfare can have two effects: If consumers change their preferences towards plant-based foods, it will decrease the carbon footprint of their diets. If they continue eating the same amount of meat, but choose products where animal welfare is put before efficiency (e.g. free range), the carbon footprint from diets will increase as the GHG emissions from these animals are often higher per kg produced. In a business-as-usual scenario the consumption of ruminant and other meat is expected to increase, and hence so are GHG emissions associated with these products. A change in diets towards more plant-based foods is estimated to reduce global food related GHG emissions by 29-70% compared with a reference scenario in 2050 (Springmann et al., 2016). If such diet changes were to take place globally, the reduced GHG emissions would also have an impact on the expected climatic changes, compared to a business-as-usual scenario. The change in attitude towards smoking in many countries (Bilano et al., 2015) indicates that a wide-spread change in consumer preferences is possible.

The impact that climate change will have on food production, will, in turn, influence the quality, availability, and price of certain foods. This will also influence the demand, and probably also the preferences of consumers, as they adapt to changes in quality, availability and prices. Climate change impacts on food production are also likely to lead to potent policy measures being taken, in order to prevent undernourishment or (worst case) famines.

Consumer preferences of production quality and production technologies (e.g. genetically modified food resources, nutrition, organic, license to produce / retailing) is another area that may have far-reaching consequences that should be assessed in scenarios of the future agricultural market and might interact with mitigation policies. This could apply to questions like whether more consumers are willing to reduce their meat consumption to reduce the CO_2 footprint or accept modern breeding technologies with higher production efficiency or more expensive organic farming for supporting more SDGs in exchange for lower taxes.

Finally, the expectations of consumers and industry for the quality of outputs and the production of feed require further research and implementation in climate assessments. This concerns the feed's energy, nutrients, amino-acid profiles, micro-nutrients, trace elements, vitamins, structural food aspects in relation to gut health, difficulties in balancing dietary requirements etc.

2.5.2 Environment: Weather, pest and disease vectors, air pollution

Effects of changes in mean temperature and rainfall on crop production are well researched, but experience tells that drastic losses in food production also depend on the timing of weather phenomena in relation with crop development: frosts, hailstorms, heatwaves, droughts, flooding, and further interactions with accessibility of fields, occurrence and transmission of pests & diseases, harvesting, crop processing costs (e.g. on-farm drying to reach target moisture content). This aspect requires more intensive research into the timing of management and its consideration in models.

The impact of climate change on pathogen, vector and wildlife host ecology and pathogen and vector spread require further research effort (Özkan et al., 2016). In particular, there is a need to use approaches incorporating ecological information into process-based modelling of pathogens and vectors. An inventory of methods used to model different pathogen species and vector ecology might reveal whether an approach used for a certain species can be used to model another species and the extent to which climate conditions may alter the spread of pathogens and their vectors. This is mirrored by little representation of susceptibility of plants and animals to pest and diseases in models. In similarity to weather, timing of pests and diseases with plant or animal development is pivotal and requires further research on possible interactions with climate change and introduction of new crop or animal breeds (or even species) into outside of their current range. Interaction of air pollutants, especially ozone, with rising temperatures also deserve further attention (Wilkinson et al., 2012).

2.5.3 New technologies

New technologies have potentially strong effects on agriculture globally when they are widely applicable. In principle, new technologies could be developed in many areas: tillage, crop production, soil fertility, inputs in terms of fertilizers, pesticides, forms energy supply, management (e.g. precision agriculture, different tillage operations, field patterns, ICT, big data use, robots, sensor), harvesting, post production, transportation, avoidance of impact on ecosystem services. New technologies might improve production, reduce losses or improve the food value chain. Even new technologies for the preparation of meals by the consumer (3D food printers) may have disruptive effects on agricultural production. New technologies may improve quantity and quality of production, the efficiency of production with respect to resource use or environmental and societal performance. New technologies developed in other areas, e.g. geoengineering for climate change mitigation, may also have negative impacts on agriculture (Yang et al., 2016). The goal of future modelling research should be to assess effects of new technologies at specific points from field to fork in terms of quality, quantity and economy of output.

2.5.4 Extreme events

What constitutes an extreme event is context dependent, and as such, there is not a universal definition of extreme events. Extreme events are addressed in a variety of ways and not consistently within models (Brilli et al., 2017). Assessing their relative threats to food security in all its dimensions is therefore difficult unless there is a clear set of metrics and definition and ranking of sub-goals (see section 2.1). Extreme events in food production may be only indirectly related to climate change, as an indirect consequence of climate change, reinforced by climate change, or by climate change mitigation. This is particularly the case for access and utilization aspects of food security (see section 2.9). Food security can be impacted by many extreme political events such as economic recession (Loopstra et al., 2015), or changes in migration patterns (Sellen et al., 2002) that may in turn cause reduced farm labour availability and prevention of harvest of economically and nutritionally valuable horticultural crops, or oil price shocks and blockages of trade routes between and within countries (Coulibaly, 2013; Tadesse et al., 2014).

Worryingly for risk assessments, an extreme event for food security can be caused by the combined impact of many smaller events that in isolation could go largely undetected. There is a lack of knowledge around the impact and probability of such clustering of fine-scale events in space or time. Crop yield failure at individual farms due for instance to localised weather events (e.g. hail), or pest and disease outbreaks could have a large impact on regional food availability or the availability of specific foods if spatially clustered. Temporal clustering of sub-standard harvests may erode food reserves and push the food system toward or past a tipping point.

In defining an extreme event by its statistical distribution, it is problematic that thresholds for calling an event "extreme" change with a moving reference period for the sample. E.g. extreme events in weather may be defined by a climatic factor in the 95th percentile of that value during a thirty-year reference period. It may, however, be an absolute temperature that implies an extreme event because it corresponds to a physiological threshold (e.g. maximum temperature for crop photosysnthesis). As weather extremes such as heat waves above 30°C become more frequent, they are, by definition, less likely to be classified as extreme statistically, while exerting an equal physiological impact on a crop plant or livestock animal. Similarly, if food security more frequently failed, it could take a greater proportion of consumers to become food insecure before an 'extreme event' was identified (in effect, 'shifting-baselines').

Models could play a stronger role in assessing not only the impacts of extreme events but also in selecting options for building in security against extreme events, e.g. mitigating drought through drainage and water storage at the same time, making feed stocks/silages of forages as well as crops, etc.

2.6 On-Farm processes (generation of outputs)

Most farm-scale models address one of two areas, management or environment, and rarely both (Hutchings and Kipling, 2014). Both areas, however, are necessary for addressing climate change impacts and adaptation and mitigation options at farm level. In this regard, farm-scale models have been reviewed by Del Prado et al. (2013), with a focus on livestock systems, and the models' capability to quantify GHG emissions, adaptation and mitigation options. They found that research is required for models to capture both short-term processes (e.g. release of NO_2 from soil — hourly) and long-term processes (land use and turnover of soil organic carbon — decades). When aiming to identify potential interactions between individual nitrogen and carbon sources of GHG emissions on-farm (studying the implications of climate change and mitigation), integrated models have to be used with a level of detail that accommodates this aim. For example, integrated models could be used to evaluate local/on-farm consequences of strategic decisions on the shift between home-grown feed resources and imported feed resources, between grazing and feed stocking or in level of farming intensity. A combined use of models for grassland, forage crops, crops, feed stocking, water management, manure management, livestock and housing needs might also contribute to improvements of accuracy and deeper insights through the multiple constraints set by the various model assumptions. Along with the increasing number of aspects included in the modelling, it will be necessary to monitor the overall uncertainty of model outputs so that the outputs remain relevant. Greater efforts are needed to close the gap between modelling efforts at the farm level adopting rather generic approaches and more detailed process-based modelling.

There is also a need to integrate economic and environmental aspects for addressing the uptake of new knowledge or policies (Del Prado et al., 2013; Rawnsley et al., 2016). Processes at farm level (within mixed farms or among specialized farms) are linked by the cycling of nitrogen, carbon (and money) and require a mass-balance approach. Here, further research is needed for improving models and obtaining data for a life-cycle analysis approach. This must be supported by farm-scale observation of data with sufficient replication (many similar farms) and range (many different farms). Improved models should also be capable of respecting constraints set by existing policies in order to assess mitigation or adaptation options. There is also a need to define what constitutes an extreme event at farm-scale. Is it the economic impact, the spatial extent of damage or the combination of otherwise non-threatening events? It is important to understand the impacts of extreme events on the physical environment (e.g., water drainage), the biological system (food and feed crops, livestock), the implications of extreme events for management and income, and their interactions in order to develop an impression of extreme event occurrence and likelihood.

An additional step is necessary for making model results more useful for implementation at farm or policy level so that climate change impacts can be tackled, while increasing productivity and enhancing ecosystem services. Producers policy-makers, as well as modellers and experimental researchers across many disciplines must collaborate (Campbell et al., 2016; Kipling et al., 2016b) in order to establish goal priority metrics and goal compatibility (see section 2.1) that can be addressed in models.

2.6.1 Below farm-scale

Below the farm scale, several aspects require further research to understand processes and represent them with suitable accuracy and certainty. These issues have been addressed in a separate publication (Brilli et al., 2017). In part they extend to the farm-level ("carry-over effects"), e.g. in the way farm management responds to impacts of extreme climatic events or pests and diseases on crop and livestock. Here, research is necessary to identify situations, when these effects dampen each other or multiply in impact at farm-level. This includes also temporal carry-over effects, when sequences of events have more than proportional impacts than the individual event. This may require incorporating crop rotations at farm level.

For livestock systems, the strong contribution of livestock production efficiency to GHG production requires incorporation of animal health, animal nutrition, consideration of variation in animal breeds and the spread of disease vectors in farm models (Özkan et al., 2016). So far, the impacts of animal health on greenhouse gas emissions intensity have been quantified only in a few studies (Macleod et al., 2016; Skuce, 2016; Özkan Gülzari et al, 2016). Williams et al. (2013) used systems-based life cycle assessment to quantify the emissions and identify the relationships between health conditions and the approaches to prevent them, but current empirical functions lack the ability to attribute the effects of heat stress on production to breed, production output, and degree of animal well-being. In the area of feed production, grassland models must become better in modelling climate change impacts on multi-species swards, nutritive quality, quantification of GHG emissions, and interactions with grassland management, especially grassland fertilization with slurry (Kipling et al., 2016b; Brilli et al., 2017).

Crop models do not yet represent the diversity of crops currently grown, in terms of either crop species or genotypes within species. Globally, the vast majority of climate change impact studies to date have focused upon four major crops; maize, wheat, soybean and rice (e.g., Deryng et al, 2014; Challinor et al., 2014). This is due to i) insufficient experimental data, and ii) knowledge gaps around current cultivation practises. There remains a limited experimental understanding of how different genotypes within crop species respond to climatic factors, particularly rare climatic extremes. Sensitivity to abiotic stress can vary between crop varieties and even with individual alleles (Barber et al., 2017) due to, for example, small differences in the diurnal timing of critical reproductive events. The controlled environment studies typically required to investigate these fine-scale responses to climatic extremes are resource intensive (Zinn et al., 2010). This can result in crop models that are parameterised using very coarse climate responses (e.g. temperature at 5°C intervals), obsolete cultivars, or simplified response parameters (e.g. in-vitro rather than in vivo temperature responses of pollen to temperature, Deryng et al, 2014). Plant diseases (Brilli et al., 2017) may also transcend to farm level as they require specific management and require robust implementation in farm management models. A further complication for conducting a risk assessment is limited knowledge of which crops and crop cultivars are currently cultivated in many parts of world (Asseng et al., 2013).

2.6.2 Effects of production and management on resource efficiency, ecosystem services, rural development

While in general yield increases can be achieved through intensification (via fertilizers, pesticides, water), it is becoming increasingly important to reconcile production with environmental and socio-economic services of agriculture. The terms ‘sustainable intensification’ (Garnett et al., 2013) or ‘ecological intensification’ (Tittonell, 2014) describe the challenge of increasing production while minimizing resource use. This may be achieved through more effective management of ecological interactions, exploiting the inherent capacity of the soils to produce, and maintaining biodiversity and ecosystem services. In addition, agricultural production is expected to deliver the basis for rural jobs, value chain creation, and recreation (Biggs et al., 2015). An integrated assessment of climate change adaptation pathways for agricultural management therefore has to capture the linkages between agricultural management practices, soil-crop interaction and crop growth processes, resource use, and impacts in terms on environmental and social development targets (Guerry et al., 2015). Such linkages and interactions vary across space and depend on local geophysical, and socio-economic conditions. Accomplishing these assessments across Europe requires corresponding funding of data collection, adaptation of models, simulations and evaluation. The simulation of complex interactions and impacts needs a range of models that cover different processes in order to generate input/output indicators. For different spatial scales (field, farm, region, country, trade union) impact themes, indicators, and data for farm models must be adapted to appropriate problem, process and decision levels. Resource efficiency, ecosystem services and rural development will have to be included in the goal evaluation metric (section 2.1) in order to organize the knowledge flow across a combination of models from management input through crop growth into environmental and socio-economic impacts at different spatial scales. New pests or diseases or epidemics can have large-scale consequences beyond individual farms and may affect regional economics if dominant crops or livestock breeds are affected. Investigating the relationships between ecological responses of pathogens (and vectors) and land use change in the context of climate change will require interdisciplinary studies. There is research need in revealing the complex interactions between different diseases, pathogens and intervention strategies, which potentially require the joint effort of multiple stakeholders including farmers, farm advisors, climate change modellers and economists. Reviewing the current knowledge on adaptation and mitigation strategies related to pathogens and vectors — especially in relation to livestock — and the potential to model their impact in practice is vital to understand the interactions among them, their effectiveness and economics consequences (Özkan et al., 2016).

2.7 Farm income (adaptation, mitigation, management)

A large area of uncertainty that necessitates further research is the response of farmers and farm management to changes in policy and climate. We focus here on crop production farms, acknowledging that intensive livestock and mixed farming systems can be even more complex.

Adapting to climate change at the farm level concerns both crop specific adjustments (sowing and harvesting dates, fertilisation, irrigation, crop protection) and adjustments in farm level production organisation (land use, resource use management, investments in technology and secondary sources of income, profits and income risks). Both crop and farm level adjustments are linked and coupled to market (input and output prices, change in demand) and policy changes.

The first aspect of an adaptation analysis that currently has significant gaps even at the farm level is uncertainty and risk analysis. Despite some literature linked to this is emerging, (e.g. Troost and Berger, 2015; Ewert et al., 2015), there are severe and demanding challenges for research. First, we consider uncertainty and risk analysis at the farm level, and then consider also market level issues.

Full and comprehensive integrated analysis of climate change adaptation at the farm level cannot rely on e.g. climate change impacts, based on modelling results for one or two crops only (see 2.6.1), even if such crop specific analyses could include all the major aspects of climate change per crop. Farmers can most often cultivate more than one or two crops and their varieties, even in boreal climates (Peltonen-Sainio et al., 2016). While dominant European crops, such as wheat and barley, have high market values and stable demand, climate change and various sustainability targets are very likely to require improved crop rotation and cultivation of more than one or two crops (Bennett et al., 2012). This is due to increased pest and disease pressure (Hakala et al., 2011), increased loss or soil organic carbon due to higher temperatures, and increasing threat of more frequent adverse events such as droughts and wet conditions (Trnka et al., 2014), implying increasing importance of water retention capacity. This, in turn, is affected by soil carbon, influenced by crop rotation (Meyer-Aurich et al., 2006).

A consistent farm level analysis needs to account for both averages and variability changes of crop yields and profitability. Risk averse farmers are interested not only in average gross margins and profits per crop, but also in their variability and covariability (Rapoport, 1998; Hardaker et al., 2007). For example, yields of spring cereals are often changing in the same direction and are thus strongly correlated, while the yields of winter cereals, oil-seeds, or forage crops are most likely less correlated with spring cereals (e.g. Lehtonen and Kujala, 2007). If the climate change implies reduced correlation — or even negative correlation — of a yield of some crop to other crops, then a risk averse farmer is likely to gain more stabilised income (and utility) when increasing land allocation to such crop. Risk-opportune farmers might consider crops with a higher chance of failure but high profits in case of success. Their strategy for maintaining a sustainable income could also include the use of financial buffer mechanisms like crop insurances or stock market instruments.

If inter-annual crop yields, and hence their gross margins, become more volatile due to climate change, then any risk averse farmer is interested in adjusting farm management to how covariability of the crop yields and and revenues will develop. This, in turn, is a challenging task since most crop modelling efforts, which can at best provide both average and covariance aspects consistently and comprehensively in different climate scenarios, have been successfully carried out only in case of a limited number of crops in individual regions (Rötter et al., 2013; Ewert et al., 2015). Crop modelling is in high demand in this, however, to account for the main drivers of crop yield changes and climate change impacts in sufficient detail. Also global circulation models for climate are many and they produce a spectrum of climate change results for individual regions and countries, in terms of temperature and precipitation changes. Hence, crop modelling is probably the way to produce a consistent set of crop specific results on changes in mean yields and their covariability.

Thus the full and comprehensive analysis at the farm level —at least for the special case of crop farms— first requires crop modelling studies focusing on individual regions, their typical soil types. This requires sufficient data on especially the most common break-crops of major crops which can offer benefits of crop rotation.

If research results on crop mean yields and their covariability are made available, farm level economic models are capable of analysing both mean and variability changes of crop yields (e.g., Liu et al., 2016). Still farm level analysis has its limitations, well perceived by farmers already. For example, local markets may be uncertain and limited and not always lucrative for e.g. break crops. There may be too little and too uncertain demand for, e.g., protein crops locally, or prices of imported protein crops are too low to cover the costs of the break crops (Sipiläinen et al., 2012). In some cases farmers may accept lower revenues from break crops in order to avoid negative effects of monocultural production, such as increasing pest and disease pressure, or decreasing organic biomass and soil organic carbon (Mandryk et al., 2014). However if the prices of break crops, limited local demand, or related marketing and other costs are clearly discouraging, not even improving mean crop yields and decreasing yield variability may be sufficient to make break crops economically profitable (Juntti et al., 2005; Sipiläinen et al., 2012).

Diverse land use and production of several crops have been traditionally seen as core means of managing risk at farms (Maynard et al., 1997). However, this assumption, or empirically proven result, in some cases, is dependent on the assumption that adding more crops in the cultivation plan would lead to reduced, or even negative correlation between the yields and revenues of individual crops. This traditional hypothesis or observed empirical result may not be obvious in the case of future climate, with crop specific impacts, or market repercussions.

This leads us to the second main research challenge. There are few, if any attempts in global economic modelling of agriculture to provide consistent results on price variability or covariability of agricultural products and inputs (Nelson et al., 2014). This is why currently one may only assume that price covariability will stay at observed levels. Assuming increasing or decreasing price (co)variability is currently problematic in analytical terms, for consistent empirical analysis.

Risk related to adverse weather events with significant yield impacts, which are likely to become more frequent in the future, or increased fluctuation of prices, both pose significant challenges for farm level analysis of adaptation. Farm level is apparently the most decisive level of decision-making where uncertainties and risks related to climate change are managed. If such research problems are adequately solved, one may find also feasible to study climate change related uncertainties and risks at higher levels of aggregation.

2.8 Challenges in large-scale integrated climate change assessments — the role of technology and yield gaps

Technological change is one of the main drivers counteracting the risks to global food security through economic and population growth and climate change (Benton et al., 2003; Hazell and Wood, 2008). In crop production, addressing the availability aspect of food security, technological change mainly refers to breeding progress, efficiency gains in fertilizer and plant protection use and machinery including digital farming. The prospects of an increasing world population go along with rising demand for food. This calls for further increases in crop yield and production. Yield increases can either be reached by closing the gap between actual and potential yield, or by lifting potential yield (Fischer and Edmeades, 2010; Zimmermann and Latka, 2016). Closing the yield gap in areas where the gap is wide could have a dramatic positive effect on global food security. A further complication for conducting a risk assessment is limited knowledge of which crops and crop cultivars are currently cultivated in many parts of world (Asseng et al., 2013). This reduces the accuracy of reference scenarios and affects comparisons with the reference scenario.

The main challenges in large-scale integrated climate change assessments refer to clarifying the distinction between technical progress in terms of breeding and decreasing the yield gap through improvements in management (Ewert et al., 2005) (Neumann et al., 2010) (van Ittersum et al., 2013). In particular, challenges are to (1) improve the representation of technical progress in the integrated assessment (Zimmermann and Latka, 2016), (2) improve the representation of management for yield gap closure (Zimmermann and Latka, 2016) and, finally, (3) establish feedbacks between crop and economic models (Janssen et al., 2011; Britz et al., 201220; Ewert et al., 2015).

First, technical progress is usually considered as exogenous (external) driver in large-scale integrated assessment (IA) studies, whereas management changes happen endogenously (Nelson et al., 2014). Exogenous yield trends are usually statistically estimated based on past yield trends and altered according to scenario assumptions (Ewert et al., 2005; Götz et al., 2016). This mechanism could be improved by representing breeding progress explicitly, for example, in the crop models.

Second, the management representation in the economic models is often rather stylized. In CAPRI (www.capri-model.org), for example, adjustments in cropping intensity (i.e. yield gap changes) are methodologically implemented by allowing regional supply models to select between two intensities, a high yield and a low yield variant for each of the crops. The mixture of both determines the final yield in a region. The endogenous yield changes are achieved through adjustments in inputs in response to price changes (Britz and Witzke, 2014; Zimmermann et al., 2017). Particularly, the simplified representation of the reaction of yields to management changes could be refined by a smoother production function representation and econometrically estimated input-output coefficients (Rutten et al.). By nature, such yield gap assessments need to be multi-disciplinary based on biophysical and economic expertise (Zimmermann and Latka, 2016). The literature already provides a number of global and European yield gap analyses, e.g. (Lobell et al., 2009; Baldos and Hertel, 2012) (Neumann et al., 2010) (Reidsma et al., 2009) (van Ittersum et al., 2013). Now, research is required for establishing smoother multi-disciplinary economic production functions.

Third, the link between crop and economic models in large-scale integrated assessment studies could be improved. The current practice is crop model results (and rarely livestock model results) are inputted to the economic models, where further endogenous adjustments take place. These are based on simplified changes in cropping intensity in response to certain market variables. For a “real” integrated assessment, in fact, the adjusted input intensities would need to be fed back to the crop model for a respective update of crop model yields, thus leading to an iterative procedure. Working toward a deeper integration of large-scale crop, livestock, and economic model would require considerable further conceptual and methodological research (Janssen et al., 2011) (Britz et al., 2012) (Ewert et al., 2015).

2.9 Challenges in reaching food security

Sufficient food production is only one essential component of food security. Food production can be stable, but an extreme economic event can result in barriers to food access and utilization (Lambie-Mumford and Dowler, 2015; Loopstra et al., 2015). To fully consider food security across its dimensions (FAO 1996), a risk assessment must include estimation of the access to, and use of, healthy and safe food, alongside a measure of variability on these dimensions (e.g. the level of certainty). These estimations are required at fine temporal scale, as food security can fail catastrophically on a within-year timescale (Dyson, 1991). What may be perceived as unsubstantial changes in food price can, when coupled with reduced income, lead to increases in the real food price (e.g. relative to income and other expenditures) and reductions in fruit and vegetable consumption as consumers substitute diverse diets for less expensive, calorie-dense alternatives (e.g., Antentas and Vivas, 2014). This can have subsequent detrimental impacts for health (Story et al., 2008). At the regional or national level, the proportion of population impacted by these changes may be strongly non-linear, due to the uneven distribution of income. Therefore, a thorough assessment of food affordability, or the price of food relative to income and other expenditures, is required to more thoroughly capture potential failures in food security across its dimensions.

3 Conclusions

The preceding sections showed, by focusing on the farm scale, that gaps in knowledge and challenges in implementation still abound for representing a clear picture of climate change impacts on food security. These challenges refer in the first place to setting priorities among competing goals together with all stakeholders groups, defining a manageable number of scenarios in order to reduce the unlimited possibilities of future development, observing interactions, feedbacks and trade-offs with other SDGs, implementing consumer behaviour, estimating effects of new technologies, considering constraints by farm economics and existing policies in modelling farm management, and assessing extreme events beyond weather impacts. Refining the modelling detail of processes to reduce uncertainty of results and analyzing which details are of lower importance for specific questions are a mainstay of progress in modelling.

The many interactions of agriculture with other sectors and the importance of food security for other SDGs have implications for how research on this topic should be efficiently organized and interact with stakeholders. For supporting policymaking there is a strong need to produce models that reflect the main components of agricultural activities, their contributions to SDGs, can produce a probability distribution for the outputs and accept a probability distribution for input variables. This would allow quantifying (to some degree) the contribution of further research to reducing the uncertainty of outputs. The activities of FACCE JPI and its knowledge hub MACSUR, collaborating with other global and national partners, provide a foundation for keeping advancing international collaboration in modelling, and provide a structure for the organisation of efforts for improving modelling for supporting stakeholders along the food value chain and policymakers in making strategic decisions.

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