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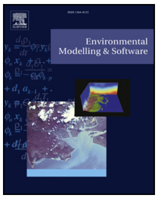

To what extent is climate change adaptation a novel challenge for agricultural modellers?

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ABSTRACT

Modelling is key to adapting agriculture to climate change (CC), facilitating evaluation of the impacts and efficacy of adaptation measures, and the design of optimal strategies. Although there are many challenges to modelling agricultural CC adaptation, it is unclear whether these are novel or, whether adaptation merely adds new motivations to old challenges. Here, qualitative analysis of modellers' views revealed three categories of challenge: Content, Use, and Capacity. Triangulation of findings with reviews of agricultural modelling and Climate Change Risk Assessment was then used to highlight challenges specific to modelling adaptation. These were refined through literature review, focussing attention on how the progressive nature of CC affects the role and impact of modelling. Specific challenges identified were: Scope of adaptations modelled, Information on future adaptation, Collaboration to tackle novel challenges, Optimisation under progressive change with thresholds, and Responsibility given the sensitivity of future outcomes to initial choices under progressive change.

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1. Introduction

Agriculture must feed a growing world population and deliver essential ecosystem services, while providing economic, social, and cultural value (Chaudhary et al., 2018; Howden et al., 2007; Thornton, 2010). Ensuring that the sector adapts effectively to the multi-faceted impacts of climate change (CC) (Iglesias and Garrote, 2015; Olesen, 2017) is therefore vital. Proactive adaptation undertaken today is likely to be less costly and more effective in reducing the societal impacts of CC than delayed or reactive responses (Stern, 2007). However, there is uncertainty around essential knowledge regarding CC impacts at local level (Diogo et al., 2017) and the effectiveness of adaptation strategies under different future scenarios (Mandryk et al., 2017; Schaap et al., 2013). Such strategies interact with a range of wider societal concerns, including the need to achieve sustainable development goals (Chaudhary et al., 2018), mitigate greenhouse gas (GHG) emissions (Del Prado et al., 2013), safeguard ecosystem services (Balbi et al., 2015; Hamidov et al., 2018), ensure food security (Godfray et al., 2010) and avoid damaging land use change (Foley et al., 2005).

Modelling is a key tool for characterising the likely environmental, economic, and social impact of CC on agricultural systems but, to reflect reality, models must incorporate adaptive responses to these impacts (Reidsma et al., 2010; Reilly and Schimmelpfennig, 2000). Models need to incorporate adaptation to test the effectiveness of adaptive responses and reveal synergies and trade-offs between adaptation to CC and other objectives (Del Prado et al., 2013; Kipling et al., 2016a; Lobell et al., 2008). In relation to any specific modelled system, CC adaptations can be autonomous (responses occurring without external intervention) or, non-autonomous (planned actions taken pre-emptively or due to experience of CC impacts) (FAO, 2007; Reilly and Schimmelpfennig, 2000). For example, in a regional scale model, autonomous adaptation might include predicted responses of farmers to environmental change (such as altering sowing dates) while a policy decision to fund irrigation systems might be a non-autonomous adaptation investigated by altering model inputs. In addition, modelling strategies investigated as potential CC adaptations might include responses to non-climatic systemic pressures with adaptive or maladaptive consequences (Grüneis et al., 2016; Mitter et al., 2018). In the context of this study, CC adaptation is defined as including: non-autonomous adaptations, any strategy explored by modellers as a potential CC adaptation, and autonomous human adaptations. Autonomous biophysical responses of the system, and actions not recognised as CC adaptations within a specific modelling exercise, are considered to be part of the context within which CC adaptation occurs.

The literature on agricultural modelling of CC impacts and adaptive responses is vast and growing (Challinor et al., 2014; Özkan et al., 2016; Rötter et al., 2018; Ruiz-Ramos et al., 2018; Wheeler and Reynolds, 2013; Zhang et al., 2017), with diversity in scope and focus. This complexity makes it hard to unpick the nature of the modelling challenges. The question arises as to whether efforts to model CC impacts and to improve agricultural modelling in general, are sufficient to support adaptive actions by stakeholders and policymakers or, whether there are agricultural modelling challenges specific to CC adaptation and thus requiring focussed attention from researchers and modellers. The aim of the current study was to search for and (if found) define challenges specific to CC adaptation modelling in agriculture. Research was based on the gathering and analysis of agricultural modellers' views of challenges to modelling agricultural CC adaptation.

2. Materials and methods

The study proceeded in three stages: i) modelling challenges were identified by modellers within workshops and analysed to identify challenge themes and categories, ii) findings were triangulated by comparing the identified themes with modelling challenges described in existing reviews. This process was used to validate the workshop data and to identify themes likely to include elements specific to modelling CC adaptation, iii) the subset of challenges considered to have CC adaptation specific aspects was considered in the light of a review of the wider literature on CC adaptation, to highlight those novel elements.

2.1. Identifying challenge themes and categories

Two workshops were held to understand and explore modellers' views on the challenges to modelling CC adaptation, bringing together researchers from across the Modelling European Agriculture with Climate Change for Food Security (MACSUR) knowledge hub (http://macsur.eu). The workshops engaged 22 modellers from 21 institutes across 11 European countries, with participants representing a purposive sample of agricultural modellers with a specific interest in modelling CC adaptation (Yin, 1989). Within this sample, 16 agricultural modelling groups were represented (Appendix A) from across crop, grassland, livestock farm-scale and economic modelling disciplines. Workshops gathered participants' views through two structured discussions in which attendees were asked to map adaptation strategies for agriculture and related modelling challenges. Participants were asked what the challenges to modelling climate change adaptation were. They recorded their ideas on sticky notes (one challenge per note) to reduce bias towards the views of vocal participants which can arise in group discussions (Kitzinger, 1995). Notes were collected and reviewed by the group to remove duplicates, clarify unclear contributions, and give participants a chance to add further ideas after considering the question during the session and in the light of other responses.

Data (responses recorded by participants on sticky notes) were analysed following a grounded-theory approach using thematic coding (Ritchie et al., 2014). Grounded theory seeks to draw information from data, rather than fitting them to a pre-conceived categorisation. Themes in the data are identified by thematic coding, for example, identifying that several contributions relate to data quality. Themes are then compared and contrasted to identify underlying characteristics linking them into broader categories relevant to the research question. In this way, categories are grounded in (derived from) the original data, ensuring relevance and openness to emerging issues (Charmaz, 2014). Qualitative approaches have been widely used to investigate the views, perspectives and characteristics of agricultural stakeholders (Mitter et al., 2018; Morris et al., 2017) but, to a lesser extent to explore agricultural research processes themselves. Exceptions include Reed et al. (2014) who used a grounded-theory approach to identify key principles of knowledge exchange in environmental management, and Kipling and Özkan et al. (2016) who analysed questionnaire data to reveal discourses underlying the perspectives of agricultural modellers on the challenges to communication with stakeholders. These examples demonstrate the practical value of grounded theory in revealing underlying patterns in complex topics.

After the identification of themes through coding of the workshop data, these themes were compared and contrasted to reveal underlying categories with relevance to the research topic (Ritchie et al., 2014). To ensure that the identified categories were robust and properly grounded in the data, results were checked by co-authors not involved in the analysis, following Bitsch (2005). In addition, intermediate findings were presented and discussed at an internal MACSUR project meeting.

An important aspect of grounded theory methodology is to ensure data saturation (Morris et al., 2017) where no new themes or issues arise from the data. To check this, specific modelling challenges were identified in the text of a global review focussed on crop modelling of the impacts of and adaptation to CC (Rötter et al., 2018). These challenges were coded to ascertain whether any new themes were present, or whether workshop themes were sufficient to accommodate the challenges described (indicating saturation). The article also defined challenges specific to modelling tropical plant production systems, providing a test of whether themes arising from the contributions of European modellers involved in the present study have relevance beyond the region.

2.2. Triangulation with previous reviews and the identification of CC adaptation specific challenges

A recent review of challenges for Climate Change Risk Assessment (CCRA) for adaptation policy (Adger et al., 2018) offered a comparison between the data from the current study, and challenges identified within a discipline focussed specifically on CC adaptation, but which encompasses change in all sectors (not only agriculture) and which may, but does not necessarily, draw on modelling. This comparison could therefore, reveal or expand on challenges related to CC adaptation itself that modellers may not have considered. Themes were identified in the review using thematic coding, following the method applied to the data from the workshops (2.1). The themes defined in this process were then compared with the themes derived from the current study to identify similarities and differences. A second set of comparisons were made between workshop data and two recent reviews of modelling challenges in the context of CC; for grassland modelling, and for animal health and disease modelling (Kipling et al., 2016b; Özkan et al., 2016). These two articles were chosen as they applied a similar approach to that used here in order to derive the challenges they presented, allowing a straight comparison with the themes identified in the current study. The disciplines of grassland and health and disease modelling lie within the broader agricultural modelling community focussed on in this study, but the reviews reflected on CC in general, only briefly treating CC adaptation. They could therefore be used to reveal which of the challenges from the current study were also wider challenges for modellers, and therefore not specific to CC adaptation modelling. In the context of a wider review of literature on CC adaptation, triangulation of these different comparisons was used to draw out specific CC adaptation challenges for agricultural modelling.

3. Results and discussion

3.1. Challenges to modelling adaptation

Grounded theory analysis of challenges to modelling adaptation expressed by modellers, identified 18 themes (see Appendix A for full description of each), and three underlying categories: Content, Use, and Capacity (Fig. 1).

3.1.1. Content of models

Many comments made by participants related to the fundamental question of how (and how well) models characterise systems. For some, the effects of external processes on systems was important "*Not possible to model landscape adaptation strategies such as creating synergies between districts for producing feeds where it is more feasible: How to assess the impacts at farm-scale?*" including top-down political influences "*Changes in policies can make previous changes in farm strategic planning (investments) useless*". Other comments highlighted challenges of modelling different types of change over time "*Solutions can be applied in many different ways (gradually, in one step, in a series of steps – 'timeframe of choices') so that the dynamism of adaptation represents another level of complexity*" and in particular, sudden change in biophysical systems "*The length and severity of extreme events may limit available management choices, and this is hard to model (e.g. a model may usually apply irrigation in a drought, but previous droughts, or a long drought may mean that irrigation water is not available)*" and changes in the adaptive choices available "*Disruptive technology: One of the areas where the struggle is predicting the arrival of disruptive technology partly because it is behavioural*". Issues were also raised relating to when choices are made "*When it becomes preferable to change the system (production) rather than to adapt*". Underlying these challenges, were those relating to modelling interactions within systems in general, e.g. "*The application of fertilisers and its effects is highly complex, for example interactions in the soil and in relation to climate change*", with adaptation adding further complexity "*Incorporate adaptation strategies adequately into models in a way that allows you to study feedbacks and side effects without prescribing too many of them as inputs, and that reflects the technical characteristics of the measure*".

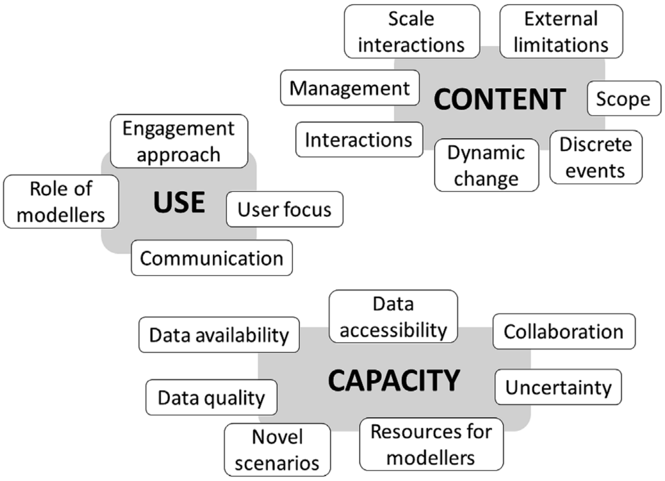

Fig. 1. Themes and underlying categories derived from workshop data. White boxes = themes; grey boxes = underlying categories.

Participants reflected on unevenness in the coverage of different systems by modelling, which may be limited in regions currently facing the most negative CC impacts "*Difficulties in modelling Mediterranean grassland systems dominated by annual self-reseeding species: the majority of models were developed for temperate grasslands*" or in relation to previously marginal production approaches that might be important adaptation strategies "*Nitrogen cycle: To create a zero-sum long term N balance - what happens in a semi-arid soil? What happens under agro forestry? What happens in ley plus arable?*". The category is bound together by a sense from the data of a research community that is itself being asked to adapt. This mirrors the progressive nature of CC, how this is changing modelling priorities, and how it disrupts a research community of previously discrete, specialised modelling groups, forcing them to broaden their focus and the application of their models (see also Section 3.1.3).

3.1.2. Use of models

Many participants raised issues that related to how modelling could and should be interpreted and applied. Some considered the need to highlight different outcomes "*Adaptation to protect ecosystem services – social context – motive of farmers (values, policy context, market failure, etc.). Demonstration of importance of these services*" while others viewed modelling as part of a wider process "*Demonstrate use of modelling in participatory projects*" with the capacity to alter the focus of stakeholders and also of research "*Modelling imagined situations to produce simulations can draw attention to a problem and stimulate the data production required to improve such estimates*". While these comments view the role of models as stimulating understanding and interest, others focussed on how to fit findings to users' needs "*Policy makers are asking 'How do we do X?' while scientists are answering 'What happens if?' questions – this can create communication problems*" and "*Understanding of the requirements of key players (policy, farmers)*". Some specific interests believed to be important for stakeholders were highlighted, along with the challenge of tailoring outputs to specific conditions "*Cooling, ventilation: Adaptation designs are very farm-specific, e.g. requirement for a very detailed design and approach*". Other comments considered how stakeholder engagement and model relevance were related "*Actors (e.g. farmers) have to be involved in the research pathway from the beginning in order to co-design research questions and co-develop win-win adaptation strategies*". A final element was the challenge of communicating findings, which may be related to the complexity of the results "*Distinguishing between descriptive forecasting and prescriptive (normative) information and results*" or the skills of modellers "*Talking is important - modellers can put too little effort into communication skills*". Some participants suggested ways to overcome communication barriers when sharing results, e.g. "*Incorporation into media products like animated films*". The Use of models category therefore has both pragmatic (What do stakeholders want? How to communicate?), and normative (What should be modelled and explored?) elements.

3.1.3. Capacity of models

In contrast to comments about what models characterise and how (Content), a distinct set of contributions were related to information and support for modelling. Many participants highlighted historical and resource-related reasons for model limitations; "*Some model limitations come from the development of models over time. E.g., [MODEL NAME] was developed when it was only technically possible to send management information to the biophysical model in (what now seems) a limited way. Management experts then moved on to other projects, and [MODEL NAME] became more biophysical*". Model evolution was seen to create problems in the capacity of successive generations of researchers to use models effectively "*Most models contain vast amounts of implicit knowledge […] Continuity of human capital is too short - this rapidly degrades the future utility of models despite huge latent potential*". Some participants referred to how model capacity can be shaped by the interests of funders, which may not align with priorities identified by researchers "*With disease, endemic diseases are more important than incursions, but less attractive to funders (e.g. liver fluke)*". Collaboration was seen as a way to tackle issues of capacity by drawing on wider expertise: "*Linking groups 'interdisciplinarily' to ensure models are fit for purpose for the end user*"

A distinct capacity-related element in responses referred to the data on which models rely. A particular focus was issues relating to data on the impacts of future CC conditions on modelled systems "*Lack of data for forage crops response to fertilizer under varied extreme event conditions*", future climatic conditions "*Focussed climate scenarios needed (e.g. northern Europe is likely to face wetter conditions and heat stress is not an issue)*" and the likely adaptive behaviour of stakeholders "*Data on risk perception of farmers: are they likely to use the strategy, why? Past experiences?*". There was awareness that data issues often related to a lack of interaction between researchers in different regions and disciplines "*There are examples of systems in extreme climates: We in north western Europe have little sense about them or data that may exist on them*" and to variation in available data quality "*Heat stress modelling work requires wider data availability to capture differences in impacts between regions (EU database). Some variation between countries can reflect differences in data quality and availability, rather than real differences in conditions*". The need for data about projected futures was raised, and particularly limitations in approaches to gaining such information "*Subjective expert knowledge on 'probability' of events and shocks*". Comments on data sometimes focussed on the need for better data sharing systems "*Inventory of modelling and experimental work to allow better access to available information*" and barriers to this "*Often one of the limits is parties holding onto data and models to protect their turf and/or obtain cash and rights*". Again, the underlying thread in this category was how tackling CC adaptation created a need to overcome the constraints of fragmented research structures.

3.1.4. Evaluation of analysis

Comparing the challenges identified here with those defined for crop modelling by Rötter et al. (2018) (Appendix C) no new challenge themes were discovered, indicating data saturation in relation to the themes and categories derived from our workshop data. Challenges from Rötter et al. (2018) aligned with a subset of six of the 18 themes identified from workshops. The article also discussed the use of model ensembles to tackle issues related to uncertainty, with this topic treated as an aspect of progress rather than a future challenge. If included as a challenge to modelling, this topic would be accommodated within the 'uncertainty modelling' theme identified in the workshop (Appendix C). As the article included specific challenges for modelling tropical plant production, the fact that no new themes were revealed also provides an indication that the themes presented here are also relevant to adaptation modelling in non-European contexts, although specific challenges within themes are likely to vary. Further investigations of challenges to modelling other non-European farming systems would be important to confirm this wider applicability of the categorisation presented.

3.2. Triangulation with previous reviews

Consolidating challenges to modelling CC adaptation into three categories (model Content, Use and Capacity) provided a useful conceptual overview. However, many issues raised related to broader modelling challenges. In particular, modelling CC impacts on agriculture is a complex challenge in itself that has been recently reviewed by a number of authors (Kipling et al., 2016a, 2016b; Özkan et al., 2016; Rötter et al., 2018). Comparisons with previous work therefore sought to further elaborate and differentiate CC adaptation-specific issues from wider modelling challenges.

3.2.1. CCRA review comparison

Comparison of the challenge themes derived from workshop data with the CCRA review (Adger et al., 2018) identified workshop challenges also recognised as issues for the adaptation (but not agriculture) specific field of CCRA for adaptation policy. The aim was to highlight challenges with potentially adaptation-specific aspects for further consideration (for full details of themes from the CCRA review and of the comparison, see Appendix D). In relation to the category of Capacity in the current study, several themes were found in both modelling and CCRA studies, specifically: *Collaboration*, *Data availability*, *Data quality*, *Novel scenarios* and *Uncertainty* (Fig. 2). Challenges identified by modellers relating to resource availability (*Resources for modelling*), and *Data accessibility* (i.e. due to communication and ownership of data rather than due to whether they exist) were not raised in relation to CCRA for adaptation policy. This difference may reflect the very specific data requirements of models, and the fact that agricultural modelling must come together across specific disciplines to incorporate CC adaptation, while CCRA is already a united community explicitly focused on this aim and working in direct support of policy. In general, these two challenge themes are clearly not a specific issue for modelling CC adaptation in agriculture, but broader challenges to model development and application.

In relation to the category of model Content, the CCRA review highlighted challenges relating to the *Interdependence* of systems, and how adaptations and their impacts cascade outwards. This theme overlaps with the modelling challenges of *Interactions*, *Scale Interactions*, *External limitations modelling* and *Dynamic change modelling*. In relation to the latter, the specific issue of accounting for *Time lags in adaptation* was highlighted. There is no CCRA theme that relates to *Discrete events*, except for a reference within the *Collaboration* theme to the benefits of linking to disaster risk management researchers. In relation to *Management modelling*, the CCRA review focused on the specific issue of *Cognitive bias*, and how it affects decision-making.

The biggest differences between the current study and the CCRA review were found in the category of Use of models. Participants in the current study expressed awareness of practical challenges relating to how to improve model relevance (*User focus*), the *Engagement approaches* that modellers need to use, the *Role of modelling* (when and how to engage) and the challenge of effective *Communication* with stakeholders. However, they did not consider how such issues might interact with differing stakeholder limitations and agendas – which was highlighted in the CCRA review within several different themes (Fig. 2, A – black boxes). These differences in relation to Use, may reflect the different characteristics of modelling versus risk assessment: In a CCRA,

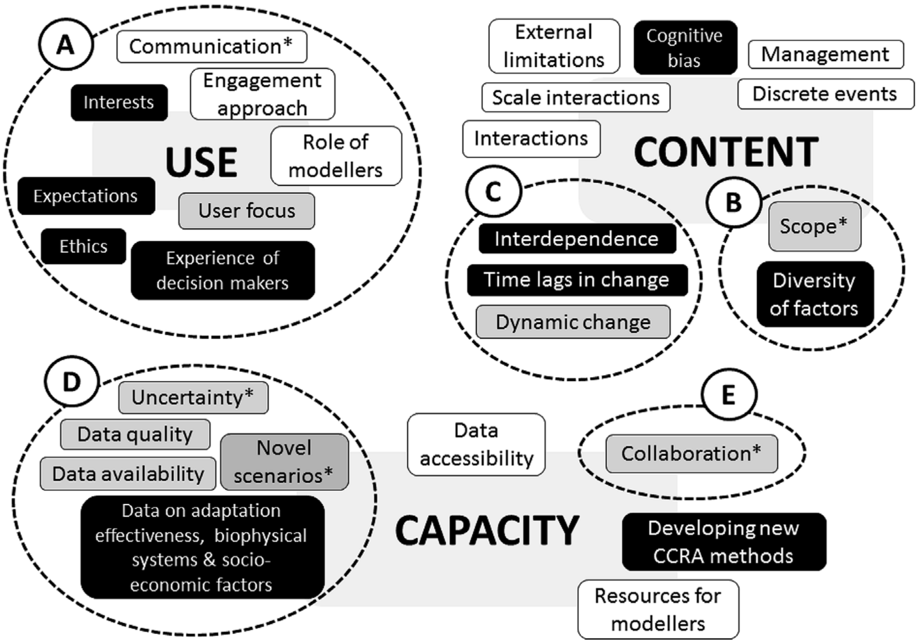

Fig. 2. Comparison of challenges identified by participants with themes drawn from Adger et al. (2018) and challenges from Kipling et al. (2016b) and Ozkan et al. (2016). Within the three categories of Use, Content and Capacity defined from the analysis of data, white and grey boxes indicate challenges identified by participants in the current study: i) listed as wider challenges for modelling in reviews (white); ii) in which some element was considered unique to CC adaptation in reviews (light grey); and iii) considered specific to adaptation in reviews (dark grey). Black boxes = challenges only raised in CCRA review. Asterisks = challenges identified by participants, and also in CCRA review. Dashed ovals delineate groupings of challenges contributing to one of the specific CC adaptation modelling challenges depicted in Fig. 3 (denoted by letters A-E).

data form the core content, with the scope of the assessment and understanding of interactions (biophysical, political and economic, across scales and sectors etc.) explicit in the subsequent interpretation of those data (an issue relating to the capacity to carry out this interpretation). In contrast, in modelling, data are required to develop and use the model (relating to the category 'Capacity') while scope and understanding of how systems work form the Content of the model. As a result, model outputs may be shared and used by decision makers without these underlying issues (contained within the model) being considered. Interpretation of results becomes a much more contested space within CCRA, with uncertainty and limitations of knowledge interacting with the sometimes conflicting subjective agendas of stakeholders (Adger et al., 2018). Comparison of the CCRA review and the present study therefore highlights the importance for agricultural CC adaptation modelling of taking better account of ethical issues relating to the presentation of findings, what they include and exclude, and with whom they are shared – i.e., issues relating to the diverse motives, perspectives and values of different societal groups.

3.2.2. *Comparison with modelling reviews*

Comparing challenges to grassland modelling and animal health and disease modelling under CC with the workshop data (Appendix D) revealed two themes highlighted only in relation to CC adaptation (not as wider challenges to modelling). The first was the development of *Novel scenarios* of future adaption (Fig. 2). *Novel scenarios* relate to the challenges of model *Scope*, with the difference being between elements of

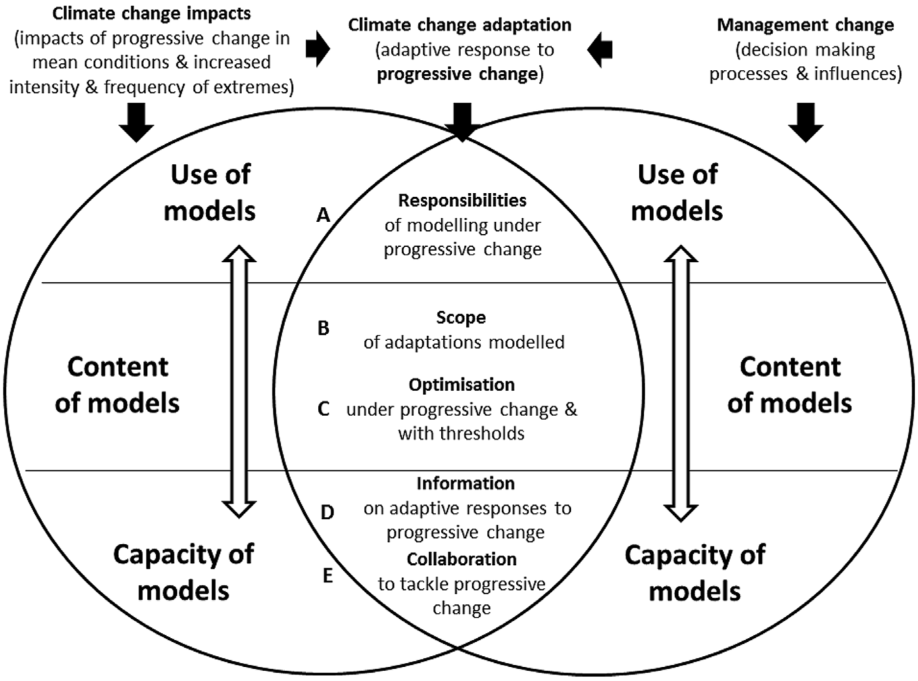

Fig. 3. Challenges for modelling CC impacts and management change and how they interact in specific challenges for modelling CC adaptation. Letters A-E reference the groupings in Fig. 2. White arrows indicate the key interaction between required model capacity and content and their use.

future change provided as model inputs (scenarios) and elements that are endogenous to models (scope). The second theme only arising in relation to CC adaptation was *Management modelling*. However, it is apparent that incorporating all relevant aspects of decision making, including *Cognitive bias*, into models is a general challenge for modellers seeking to represent any form of decision making. Studies of approaches to incorporating management into agricultural models (Moore et al., 2014; Robert et al., 2016) suggest that technical solutions exist in modelling to characterise adaptation, including constraints and changes that take place over time but, that actually representing proactive management is difficult. The fact that *Management modelling* was not framed as a general challenge in the reviews used in the comparison exercise, may relate to their focus on biophysical challenges, reflecting the implicit nature of decision-making assumptions in biophysical modelling (i.e. as rational responses to biophysical cues with perfect knowledge). This view is reinforced by the consideration in both reviews of *Interactions* between management and biophysical and economic systems, suggesting a greater focus on biophysical impacts and triggers of choices, than on characterisation of the decision-making process itself. Again, although *Interactions* modelling was considered as both a general and an adaptation-specific challenge in the reviews, improving how the *Interactions* of biophysical, economic and management systems are characterised is a general modelling challenge, with only the *Scope* of the systems modelled increasing to facilitate the modelling of novel adaptations. *Data accessibility* was another theme identified as a challenge for both general and CC adaptation modelling in the grassland and livestock health and disease reviews (the need to collate available data on future adaptations). However, overcoming issues of *Data accessibility* (ownership, sharing) is clearly a general challenge for modellers, and no specific elements of it were detailed in the reviews, or the literature.

Taking account of the discussions above, ten of the original challenges were either, not mentioned in the modelling reviews, only mentioned as general challenges to modelling under CC, or were determined to be general after further consideration (Fig. 2, white boxes). A CC adaptation specific element was suggested for three of these (Fig. 2, A – white boxes) as a result of their relation to the CCRA challenges associated with subjective aspects of dealing with stakeholders. Seven more of the original challenges were given both adaptation-specific and wider relevance (Fig. 2, light grey boxes). Determining the precise nature of the adaptation-specific elements within these challenges, required further consideration in the context of understanding from the wider literature, which is the focus of the following section.

3.3. *Identifying challenges specific to modelling adaptation*

The challenges identified in the previous section as having CC adaptation-specific elements, as well as associated themes from the CCRA review (Fig. 2., boxes within dashed ovals) are explored below in the light of key characteristics of CC adaptation, in order to focus on the underlying specific issues they present. Climate change differs from most other issues in that it overlays pre-existing socio-economic (Iglesias and Garrote, 2015) and environmental challenges, and represents a progressive and sustained change over time. As CC affects the biophysical systems on which we rely in multiple ways, it produces cascades of interacting impacts and feedbacks within and between sectors, making studies of CC issues particularly complex (Terzi et al., 2019). So, while other types of change affecting farming may also be progressive (e.g. increasing demand for meat and dairy products, advances in technology) CC is unique as a sustained, progressive change in the biophysical systems that farmers rely on, rather than just in the socio-economic context in which farming takes place. Path dependency in relation to processes of economic and political change over time, including in agricultural systems (Kay, 2003) (see Martin and Sunley (2006) for a critical review) means that our iterative responses to progressive CC may lead us down particular pathways, each with different implications for different societal groups, regions and biophysical systems. For example, investment to install and improve irrigation systems may make increasing crop water supply more cost effective for a farmer than changing towards more water efficient systems as CC advances, with implications for other water users and the environment. In Sardinia, Dono et al. (2016) found that intensive dairy farming reliant on irrigation systems is likely to be less vulnerable to CC than traditional, low input sheep production reliant on natural water supplies. Therefore, pathways of adaptive response to progressive CC need to be explored in order to facilitate informed and reflective decision making that take such issues into account. In this light, the *Scope* of models to explore the future consequences of CC adaptation strategies is revealed as a CC adaptation-specific element of the workshop theme of *Scope* (Fig. 3, B).

The issue of path dependency is also relevant to the ‘Use of models’ challenge category. In the literature on CC adaptation, even the need for intervention to ensure agricultural adaptation to CC is contested, with some suggesting that market forces will automatically adjust systems to change, while others argue that progressive CC will require well-planned responses beyond the autonomous, incremental change already undertaken by agricultural stakeholders (Anwar et al., 2013; Reilly and Schimmelpfennig, 2000). Relying on autonomous responses or intervening to completely manage CC adaptation, are two extremes in a continuum of approaches. Which adaptive pathway (different types of planned response or, reliance on autonomous change) appears most favourable depends on chosen system boundaries (e.g. biophysical processes, economic processes, social processes) and the nature of CC change (Reilly and Schimmelpfennig, 2000) but, also on desired outcomes and on whose desires are considered. Although profit or production maximising objectives may be assumed in ‘hard systems’ (van Paassen et al., 2007) research approaches, this assumption has been described as representing an ‘implicit sociology’ (Jansen, 2009) of unexplored motives and opinions. If particular motives and objectives for change have already been assumed in a model, this represents a move towards more instrumental engagement with stakeholders (to improve research outcomes or increase the implementation of recommendations) and away from normative engagement (involvement of stakeholders and incorporation of their views and needs as a right) (Reed et al., 2009). Using Freeman's (1984) classification of affected and affecting stakeholders, this focus shifts attention from those who may be affected by change, towards those that can affect change. In this context, and given that the quantification of information (e.g., in models) is understood to fundamentally alter how things are perceived and valued (Espeland and Stevens, 2008) it is important that the aims modellers focus on, what models include, who they are for, and how they are communicated, are critically reflected on by modellers in general. Within the current study, the more normative aspects of the ‘Use of models’ challenge category reflected awareness among modellers of the potential for models to affect the direction of choices (including adaptive responses) and of how, in some cases, modellers are facing the challenge of assuming new roles, e.g. recognising a “*Paradigm shift in the research praxis: from observer to co-researchers/knowledge brokers*”. Much previous work considers these issues, with recent reviews focussing on best practice in stakeholder involvement, model development, use, and evaluation (Fulton et al., 2015; Hamilton et al., 2019; Jakeman et al., 2006; Voinov et al., 2016) including the development of specific engagement processes drawing on understanding of ‘soft systems’ approaches (Martin, 2015). However, with pathway dependency in the context of progressive CC, the potential impacts of model findings beyond the implementation of a given modelled choice, add an extra dimension to issues of model use. This additional element can be seen as a CC adaptation-specific challenge to model use.

As discussed above, CC adaptation modellers (including biophysical modellers as well as bio-economic modellers) need to consider how social conflicts, power relations and sectoral interests may influence their work and its use (Lang et al., 2012; Newell and Taylor, 2018; Reed et al., 2009) in the context of progressive CC and escalating adaptive responses. Such considerations enable modellers to recognise the implications of their focus (on which stakeholders, which objectives, which adaptations and which impacts) and to identify ways to ensure that the wider context of non-modelled strategies and impacts is conveyed to stakeholders. This may be carried out by the modellers themselves where they have the required expertise and sufficient resources but, may also be achieved through *Collaboration* with social scientists, to try to avoid unintended consequences arising from the use of model outputs, and to achieve best practice (Fig. 3, E). Taken together, these considerations represent the specific CC adaptation aspects of the challenges of *Communication*, *Engagement approaches*, *Role of modelling* and *User focus* grouped as 'Responsibilities of modelling under progressive (climate) change' in Fig. 3, A).

Related to the progressive nature of CC, and adaptive responses to it, a second key characteristic of CC adaptation was revealed explicitly in workshop data. Modellers expressed the need to better understand and incorporate likely stakeholder choices under progressive CC in which their expectations and experiences of CC evolve over time, distinct from likely responses to other types of change (such as one-off shocks or opportunities to increase efficiency). One participant, for example, highlighted the importance of understanding "*Reasons or other triggers for farmer decisions on the number of cattle they have and the type of grassland management they apply, and the point when they begin to care about climate change and take action*". Addressing this issue, which contributes to the adaptation-specific elements 'Optimisation' and 'Information' (Fig. 3) of challenge themes in groups C and D in Fig. 1, requires the development of CC adaptation scenarios which are relevant to likely future conditions, and which provide data about the context of decision making and (depending on the type of model) define at least some aspects of decision making itself. Constructing adaptation scenarios is complex, not least because of the issue of path dependency in iterative adaptive responses to progressive CC, discussed above. In addition, choices are likely to be affected by dynamic changes in stakeholder understanding as conditions change (Anwar et al., 2013). Data for scenarios may come from social science models or, be gathered from stakeholders or experts, and will therefore incorporate *Uncertainty*. In addition, data needed for scenarios includes information on the likely efficacy and impacts of adaptation strategies themselves, which can also be considered to be CC adaptation-specific. Given that participants in the current study highlighted the limitations to the data on adaptation efficacy, including relating to reliance on expert views, *Uncertainty* about the likely effectiveness of CC adaptation strategies can also be considered an adaptation-specific challenge within the cluster of challenges relating to Information available for model development, testing and use (Fig. 3, D). However, uncertainty relating to models themselves is common to modelling in general, while issues around the quality of data from climate models are important for both adaptation and CC impact modelling (Cammarano et al., 2017). Scenario development therefore brings together the CC adaptation-specific elements of *Data availability and quality*, *Uncertainty* and *Novel scenarios*, as 'Information on adaptive responses to progressive change' (Fig. 3, D).

Under progressive CC, the period over which stakeholders seek to optimise systemic outputs is important, as long-term and short-term goals may not align. How this trade-off is viewed is likely to alter with the considered time periods or the assumed pace and certainty of CC (Reilly and Schimmelpfennig, 2000). This is a specific challenge for CC adaptation modelling with the goal of Optimisation (Fig. 3, C), and represents the CC adaptation-specific aspect of *Dynamic change modelling*. Recent work has started to consider the application of approaches from other disciplines to agricultural settings, in order to build understanding of how changes in the efficacy of CC adaptations over time, and uncertainty in conditions and outcomes, can be incorporated into assessments of adaptation strategies (Dittrich et al., 2017).

Barriers to inter-disciplinary research collaboration have been well documented (Siedlok and Hibbert, 2014) and the need for coordination across disciplines and institutes to tackle CC challenges has been recognised (Soussana et al., 2012). Key to challenges A and C (Fig. 3), is *Collaboration* with social scientists with expertise in managing stakeholder engagement (Nguyen et al., 2014; Reed et al., 2014) and particularly those with expertise in normative and critical engagement approaches. However, inter-disciplinary research communities require time, resources, appropriate structures and the application of specific skillsets to flourish (Kipling et al., 2016c; Tomassini and Luthi, 2007). Initiatives such as MACSUR and the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al., 2013) have driven progress in agricultural model development and use (Ewert et al., 2015; Sándor et al., 2017) and supported the application of inter-disciplinary expertise to region-specific CC issues (Dono et al., 2016; Özkan Gülzari et al., 2017; Schönhart et al., 2016).

The need to characterise a wider range of sometimes transformative adaptations in agricultural models, makes it essential to include, smaller and geographically marginal research groups in inter-disciplinary networks, to capture the diversity of expertise in the research community. These groups are vital to fully leveraging existing expertise, along with 'core' research groups that may find it easier to engage (Saetnan and Kipling, 2016). Although differences in context may prevent data on management responses to CC conditions in one location being used as a reliable predictor of change in another (Reilly and Schimmelpfennig, 2000), linking local research expertise across regions offers the opportunity to explore novel solutions, cross-pollinating ideas between scientific communities within and between disciplines. The need for integrated modelling approaches to investigate CC impacts and adaptation has been widely recognised (Reidsma et al., 2015a,b; Rötter et al., 2018), and the closer involvement of stakeholders in modelling processes is vital to the generation of model outputs with real-world relevance (Bellocchi et al., 2015; Hamilton et al., 2019). The distinct aspect of *Collaboration* for CC adaptation (Fig. 3, E) is therefore the urgency of the need to work together (resulting from the progressive nature of CC) (Hallegatte, 2009), focussing efforts on the specific challenges to agricultural modelling identified above (Fig. 3, A-D).

Illustrative reviews of the five CC adaptation-specific modelling challenges identified (Fig. 3) are provided in Appendix E, giving richer descriptions of how they are tackled by specific modelling communities.

4. Conclusions

This study sought to answer the question, to what extent is CC adaptation a novel challenge for agricultural modellers? The findings indicate that there are a number of CC adaptation specific aspects to the challenges of adaptation modelling identified by modellers. Within the three challenge categories of Use, Content and Capacity derived from the data, the theme of creating *Novel* (adaptation) *scenarios* was found to be entirely specific to CC adaptation modelling. Seven challenge themes, such as *Resources for modelling* and *Scale interactions*, represented essential pre-requisites for CC adaptation modelling but, were not considered specific to it. Ten other themes were considered general modelling challenges but, with CC adaptation-specific aspects. Most fundamentally, the importance of understanding and managing the influence of model focus, limitations, use and presentation on adaptive responses and their consequences was highlighted for both, bio-economic modellers and biophysical modellers. CC adaptation modelling draws agricultural modellers into social and political contexts in which their approaches and findings affect who wins and who loses, what is valued and what sacrificed, in the adaptation of agriculture to progressive CC. In modelling CC adaptation in agriculture, there is a need for the agricultural modelling community to focus on the aspects of model content and capacity relating to scope, optimisation, and information, on collaboration across disciplines and institutes, and on the responsibilities of modelling evolving responses to progressive CC.

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Appendix A. List of models with which workshop participants were associated

The models listed were not used as part of this qualitative study of modellers' views. The range of models is included to give an idea of the scope of disciplines and expertise represented by workshop participants and includes capacity to model a range of systems (crop, grassland, livestock and mixed) at a range of scales.

Type	Name	Focus
Biophysical	Eco-DREAMS-S	animal
	DSSAT Platform	field
	PaSim	field
	FarmAC	whole farm
	Holos Nor	whole farm
	Melodie	whole farm
Economic	PAFAMO	whole farm
	Scotfarm	whole farm
Biophysical & economic	Dairy Wise	whole farm
	FarmDesign	whole farm
	FSSIM	whole farm
	MODAM	whole farm
	DiSTerFarm	whole farm/regional
	SFARMOD	whole farm/regional
Biophysical & economic (coupled)	MAgPIE	regional
	PASMA	regional
	FAMOS	whole farm

Appendix B. Challenges to modelling adaptation: Theme descriptions

The sections below describe each of the initial challenge themes coded in the data.

Data accessibility

This theme relates to data ownership and its effect on the ability to use data that have been collected for modelling work. Data has a value to those who hold it, which may mean that it is not used to the full extent possible: "Intellectual property and 'turf'; secrecy and privacy: often one of the limits is parties holding onto data and models to protect their turf and/or obtain cash and rights" Limited accessibility may also be a more straightforward issue of communication and knowledge, with modellers who have many demands on their time looking for: "Data capture from readily available sources to reduce time spent getting outputs" To tackle this challenge, the need for shared resources was highlighted: "Inventory of modelling and experimental work to allow better access to available information"

Data availability

Limitations in available data were commented on with respect to most aspects of adaptation modelling (Table B.1). The examples in the table indicate the division by the part of the system (management, economic, biophysical) and by different data types relating to future and current systems.

Table B.1
Types of data availability challenge

Data type	Management	Economic	Biophysical
Current systems	Data on risk perception of farmers: are they likely to use the strategy, why? Past experiences?	Information on economic costs of disease and treatment	Limited knowledge on the interactions between grassland productivity and associated ecosystem services
Different systems	Few long term datasets on Mediterranean grasslands Lack of data for low input grassland systems		
Different systems as predictors of extremes	Lack of data for forage crops response to fertilizer under varied extreme event conditions there are examples of systems in extreme climates: We in NW Europe have little sense about them or data that may exist on them		
Different scales			

(*continued on next page*)

Table B.1 (*continued*)

Data type	Management	Economic	Biophysical
	Scarcity of data is an important problem – we need to know what the ‘business as usual’ state of a farm is Usually very few data on management practices and productivity at territorial scale		
Future predictions	Cost and availability of new technologies (e.g. breeds, soil management options). Also, the change in management required (e.g. new feed regime for new breeds)		Focussed climate scenarios needed (e.g. Northern Europe is likely to face wetter conditions and heat stress is not an issue) Limited knowledge on the interactions between grassland productivity and associated ecosystem services

Data quality

Some modellers raised the issue of data quality, with respect to both standards and uncertainty: “Heat stress modelling work: requires wider data availability to capture differences in impacts between regions (EU database). Some variation between countries can reflect differences in data quality and availability, rather than real differences in conditions “Subjective expert knowledge on 'probability' of events and shocks”

Collaboration

Participants identified issues of a lack of interaction and understanding between modellers in different communities – for example, between disease modellers and other agricultural systems modellers as a particular issue: “Disease modellers do not consider other modelling groups as potential users of their models/outputs. There is a gap between the modelling communities - important challenge for modelling adaptation”. And a lack of interaction between empirical researchers and modellers was also raised as a challenge: “No insight or insufficient insight on data availability from other disciplines”. Several participants highlighted the need for work across disciplines, and this was associated with the need to provide models that met the requirements of users: “Linking groups 'interdisciplinarity' to ensure models are fit for purpose for the end user”. Collaboration is underpinned by the need to improve how information about models (source codes etc.) is shared between researchers.

Communication

Modelling can produce complex findings that are a challenge to communicate to end users, with certain procedures not intuitively understandable for non-modellers: “Comprehensible sensitivity analysis”. Participants recognised the importance of communication skills in relation to ensuring outputs are easy to take in for different groups: “Policy makers want to receive a simplified summary of key outputs, not to be given complex model details. Other stakeholders also require simplified outputs. How can we make material digestible for stakeholders?” “How to communicate suggested feed changes to farmers”. Communication skills were emphasized as a challenge: “The process of transferring information might limit its accessibility [for stakeholders]. Care is needed in the communication process”. And also the importance of more integrated engagement to enable users and modellers to understand each other better: “Organising dynamic learning and communication processes”.

Discrete events modelling

One-off or extreme events are shocks to a system that may be hard to predict: “Risk and timing of extreme events”. And the effects of which may alter both, future states of the system, and the ability of decision makers to implement adaptation options: “The length and severity of extreme events may limit available management choices, and this is hard to model (e.g. a model may usually apply irrigation in a drought, but previous droughts, or a long drought may mean that irrigation water is not available”. Discrete events also include the challenge of modelling ‘threshold’ changes in behaviour – the appearance and implementation of a new disruptive technology or the point at which stakeholders move from adaptation of current systems to transformation to new systems – in relation to causes, timing and impacts of such changes: “Disruptive technology: One of the areas where the struggle is predicting the arrival of disruptive technology partly because it is behavioural (for example, a transition to food derived from bioreactors)”.

Dynamic change modelling

Adaptations can be implemented in different ways, which are likely to influence how they affect the system, and this presents a challenge for modelling: “Solutions can be applied in many different ways (gradually, in one step, in a series of steps – ‘timeframe of choices’) so that the dynamism of adaptation represents another level of complexity for modellers”. At the same time, biophysical processes themselves may occur over different (short- and long-term) time scales, which can be hard to capture: “Short term (eg annual) versus long term (eg decadal) simulations, e.g. soil carbon, soil organic matter (long term dynamics) not well addressed”.

Engagement approach

Participants highlighted the challenge of engaging in meaningful ways with stakeholders: “How to build long term connections between interested farmers and scientists that go way beyond usual project durations”. A range of approaches and tools for improved engagement with stakeholders was shared, for example: “Typical farms as anchor for simulating and presenting my results”. “Thinking about a game in which effects and feedbacks can be explored in a kind of 'what happens when' machine”.

External limitations modelling

This theme focuses on changes to policy or biophysical constraints beyond the system that affect the implementation of adaptation options and its consequences: “Policy limitations to model adaptation strategies: change feeding increases milk yield. But, milk quota”. “Consideration of temporary regional constraints (e.g. regional silage market in case of drought)".

Interactions modelling

This theme encompasses challenges relating to i) a lack of underlying understanding of the interactions between factors and mechanisms in agricultural systems: "Too many interacting factors and interacting mechanisms are still not well enough understood to be modelled (e.g heat stress on animal productivity includes many confounding effects and studies generally do not separate these effects sufficiently" ii) challenges relating to the computational power required in characterising complex interactions involving a number of inter-dependent types of mechanism: "Computability: To integrate inter-dependent: sectors, scales (spatial) ecosystem services, scales (temporal) adaptations, future scenario space, uncertainty etc.". These issues relate to biophysical interactions: "Grassland models are not able to simulate the diversity of species and inter-specific interactions that characterise grasslands", to economic and management interactions – such as the cost/availability of novel options and the changes in management required when they are implemented: "Cost and availability of new technologies (e.g. breeds, soil management options). Also including the change in management required (e.g. new feed regime for new breeds)" and, to the effects of implementation on the biophysical system: "The application of fertilisers and its effects is highly complex, for example interactions in the soil and in relation to climate change", and finally to feedback, arising from management changes: "Incorporate adaptation strategies adequately into models at all: in a way that allows you to study feedbacks and side effects without prescribing too many of them as inputs, and that reflects the technical characteristics of the measure".

Management modelling

This theme refers to the challenge of understanding and then modelling the decision to implement change – what factors (values, knowledge, age, economics) influence these stakeholder choices, and how can these be incorporated into models: "Adaptation is related to the perception of farmers and their sensitivity to change in a specific aspect of management (e.g. they are likely to be more willing to change some practices than others). The uptake of adaptation measures is therefore dependent on culture and knowledge as well as external risk". Differentiation was made between reactive and proactive change: "Farmers have to face actual events, not the risk of events. After such events a range of actions will be required for a system to recover; these represent 'reactive' adaptation, which is not the same as pre-emptive adaptation to reduce future impacts". With a question as to how biophysical models can incorporate adaptation when choices to adapt are made in advance of biophysical triggers to change: "How do biophysical models include the costs of anticipatory strategies?".

Novel scenarios

Under climate change models will be faced with the need to characterise new circumstances and their impacts: "Under climate change, relationships between variables may not remain the same (e.g. under more extreme conditions than tested for) and we need to try to understand these potential changes" One challenge is to represent the impacts of climate change on the biophysical system: "Differential effect of increasing CO2 on mixed swards". And their downstream impacts on production: "Roughage quality analysis not future proof (mixed sward quality under climate change)". On top of this, is the need to then understand how the implementation of adaptation options will affect such changed systems: "Model limitations for allocating land to feed types (plus protein feeds?) e.g. forage versus cereal crops (adaptation through changing feeding patterns)". This may include the introduction of new production options: "Nitrogen cycle: To create a zero sum long term N balance - what happens in a semi-arid soil? What happens under agro forestry? What happens in ley plus arable?".

Resources for modelling

This theme covers three main areas. 1) The way that models develop over time, and how this affects their capabilities (e.g. if some parts are based on older research) and the capacity of their users to understand them: "Some model limitations come from the development of models over time. For example, [MODEL NAME] was developed when it was only technically possible to send management information to the biophysical model in (what now seems) a limited way. Management experts then moved on to other projects, and [MODEL NAME] became more biophysical". Especially when the agricultural modelling field may not have the space to nurture many careers: "Agricultural systems modellers: very narrow resource pool, very different funding, too few can form a career at the coal face - many just pass through". 2) Issues relating to computability, and the need to incorporate more and more complexity while handling the trade-off with usability: "Computability: To integrate inter-dependent: sectors, scales (spatial) ecosystem services, scales (temporal) adaptations, future scenario space, uncertainty etc.". Finally, modelling resources may not be distributed equally across specific topics, and this unevenness may not reflect the importance of individual topics in relation to adaptation: "With disease, endemic diseases are more important than incursions, but less attractive to funders (e.g. liverfluke)".

Role of modellers

Focuses on the different ways in which modellers engage with real world problems. This includes various roles for model outputs to demonstrate the importance of something, to allowing comparisons of systems (benchmarking) to informing decision making, and in the development of new ideas, and also includes changes in the role of the modellers themselves (not just their tools): "Paradigm shift in the research praxis: from observer to co-researchers/knowledge brokers".

Scale interactions

The theme consists of challenges to modelling how change at one scale affects that at another, including the need to predict the farm-scale impacts of wider changes: "Not possible to model landscape adaptation strategies such as creating synergies between districts for producing feeds where it is more feasible: How to assess the impacts at farm-scale?". And the importance of scaling up detailed farm-level modelling to provide regional scale predictions: "Upscaling issues e.g. modelling at farm scale and […] impacts at landscape scale". Participants highlighted how such effects cross the boundaries between economic and biophysical modelling: "Need to start with farm-level adaptations. Farmers may observe regional water issues and pay for own storage, or find it better to reduce water dependence by using different crops etc."

Scope

This theme focuses on the extent to which models cover different regions and systems "Difficulties in modelling Mediterranean grassland systems dominated by annual self-reseeding species: the majority of models were developed for temperate grasslands (mainly dominated by perennials". Elements of systems: "Demonstrate how biodiversity impacts productivity, e.g. by showing influence of pest predation on yield, and impact of beneficial fauna on this: Acceptance and better understanding of feedback effects between production, biodiversity and ecosystem services (societal value)". And the extent to which they are able to span (or take into account) interactions between biophysical management and economic elements of change, which are central to understanding adaptation: "Biophysical models ignore economic life; e.g. if all farms use more imported feed, then feed prices will rise, people will move out of farming, and animal prices will fall. These are important interactions requiring anticipatory actions by farmers to minimise costs".

User focus

These challenges related to the need to ensure models and their outputs were mindful of the needs of stakeholders, who may differ from modellers in relation to the timescale they are considering, or type of questions they want answered: "Policy makers are asking 'How do we do X?' while scientists are answering 'What happens if?' questions – this can create communication problems". The theme includes the challenge of providing tailored models: "Cooling, ventilation: Adaptation designs are very farm-specific, e.g. requirement for a very detailed design and approach". To the extent of modelling on demand: "Applied research by demand (i.e. farmer associations demanding to play with their real data)". Modellers need to consider who their users are and what they need, and working with them can be part of achieving this: "Define end users, target groups and work with them throughout". Finally, some participants referred to the need to ensure that outputs were interpreted correctly: "Distinguishing between descriptive forecasting and prescriptive (normative) information and results".

Uncertainty modelling

The need for models to be able to deal with uncertainty from biophysical and economic systems, and from models themselves was commented upon by several participants, e.g. "Integration of deviation coming from the biological world in the correctness of the model".

Appendix C. Comparison of workshop findings with a review of crop modelling in the context of climate change impacts and adaptation (Rötter et al., 2018)

Specific challenges were extracted from the text of the review article and coded, contrasting and comparing these challenges with workshop data and themes, to develop or add themes where required. No new themes emerged from the data, with all challenges being compatible with themes identified from workshop data without further development (Table C.1). The article identified some challenges specific to tropical systems (Table C.1); these challenges were also compatible with themes identified from analysis of workshop data.

Table C.1
Text relating to challenges to modelling agricultural impacts of and adaptations to climate change identified by Rötter et al. (2018) and its relation to themes identified in workshop data. **TS** = challenges identified by Rötter et al. (2018) as specific to tropical plant production systems.

Text extracts from Rötter et al. (2018) relating to modelling challenges	Themes
Economic models need to be combined with Crop Simulation Models in whole-farm assessments to better evaluate management practices	Collaboration; Interactions
Management and land use does not only respond to climate change, but also to changing socio-economic conditions, such as liberalization of markets or changes in dietary habits. Crop Simulation Modelling thus needs to be integrated into a larger modelling framework.	Collaboration; Interactions; Scale interactions
Statistical Models are constrained in many cases by the availability of adequate, representative yield data	Data availability; Data quality
Substantial mismatches between Crop Simulation Models and Statistical Models may indicate knowledge gaps regarding the mechanisms/ processes that cause under-/overestimation of yield, et cetera	Data availability; Interactions
Despite some efforts, the effect of tillage on carbon storage has so far only been modelled with limited success, mainly due to insufficient field data to develop mechanistic descriptions in the models	Data availability; Interactions
At larger scales, Crop Simulation Modelling is severely hampered by lack of data for parameterization and calibration and management systems are often unknown. Large uncertainties persist — especially related to variability in managerial practices and spatial response patterns.	Data availability
Likewise, important tropical crops have been much less investigated in experiments regarding their exposure to agro-climatic extremes than those for temperate systems. Even with some progress in data availability, there is a need for both — more experiments and modelling — (as propagated by TROPAGS, see Fig. 3) to understand the underlying mechanisms. **TS**	Data availability
A key constraint to realistically upscaling the productivity of such systems (and how it is affected by climate change) to region level is, for instance, that fields of smallholder systems are not clearly defined, and a wide range of crop types can be found within a field. **TS**	Data availability
Besides improving crop models, fast track methods are needed to characterise and inventory smallholder fields as a basis for upscaling. Thereby the typical simplistic focus of modelling climate change impacts on sole crops (usually maize) in smallholder systems of Africa can be overcome. **TS**	Data availability
We need much better understanding of how climate effects scale with changes in low input systems **TS**	Data availability
Still, by far the majority of Crop Simulation Models deal with single season, single crop runs	Dynamic change
There is also an increasing interest in the role that agricultural management has on environmental impact, such as carbon sequestration or GHG emissions. However, carbon stocks need years to build up, thus long-term simulation over multiple years that also reflect the current deviation from the equilibrium state are necessary to capture that	Dynamic change
While ensemble approaches helped to make model predictions more robust and quantify the uncertainties, the next logical step was to improve responses to heat and the fundamental temperature functions in individual models, to eventually reduce the uncertainty by proposing improved functions and parameterization	Interactions modelling

(*continued on next page*)

Table C.1 (*continued*)

Text extracts from Rötter et al. (2018) relating to modelling challenges	Themes
… and also lack information on critical interactions of factors such as weather, soil and management practices	Interactions modelling
So far, crop models are not capable of capturing the multi-species interactions within one 'field' and the associated services delivered **TS**	Interactions modelling
Moreover, many systems are integrated crop-livestock systems, which makes the common use of the model output variable 'yield produced per unit area' difficult **TS**	Interactions modelling
One advantage of this method (use of statistical models) is that it inherently covers also indirect yield limiting factors, which are linked to climate variables, like pest and diseases. Process-based crop models so far largely ignore their effects, and thus fail to estimate farmer yields accurately in regions and years where biotic stresses are significant	Scope
While these (multi-model ensemble approaches) can be the basis for systematically exploring critical parameters and assumptions, they do not compensate for exploring missing mechanisms	Scope
Global model runs suggest strong effects of climate change on the crop production systems in the Global South, especially in Africa. However, such runs were done mainly for water limited and/or nutrient-limited yield, hence, with yields not limited by biotic stresses. That makes the results of little use to understand the actual effect of climate change on these systems, as many tropical plant production systems are heavily restricted by combinations of severe abiotic and biotic stresses **TS**	Scope
Many tropical systems are arguably more complex including agroforestry/intercropping. Unfortunately, crop models have been rarely tested/applied in such systems. **TS**	Scope

Appendix D. Comparison of workshop findings with a review of challenges for climate change risk assessment (CCRA) for adaptation policy (Adger et al., 2018) and challenges identified by Kipling et al. (2016) (grassland modelling), Özkan et al. (2016) (livestock health and disease modelling)

D1. Themes from the Adger et al. (2018) review of challenges to CCRA for adaptation policy

The themes below summarise the text of the Adger et al. (2018) review, gathering it into intuitive groupings that enabled easier comparison with the challenges identified in the current study. The themes were extracted from the paper using a thematic coding approach (Ritchie et al., 2014). Themes were then compared with challenges identified by modellers in the workshops, to highlight any CC adaptation-specific issues that modellers also need to tackle (gaps in coverage of identified adaptation modelling challenges). How the CCRA for adaptation policy themes, and those identified by modellers, overlapped and complemented each other, is described in section D2 and Table D1 (below) and explained and visualised in main text (Fig. 2). In Fig. 2, some of the themes below are grouped according to their type, indicated in brackets next to their title (e.g. incorporating biophysical knowledge into CCRA relates to the availability and quality of data).

Biophysical knowledge (data availability)

Biophysical systems will respond to climate change in complex ways that interact across systems and over different time scales, including feedback effects on climate change itself; these interactions are not fully understood, including for example potential for critical transitions. Recent studies provide improved assessments of the extent to which specific events can be attributed to anthropogenic climate change and predictions about the magnitude and frequency of extreme events.

Cognitive bias

Human choices are often made using mental short-cuts which allow decisions to be made despite limits to available information of the ability to gather and process it. These cognitive factors can bias the choices according to pre-existing preferences, and can lead to inconsistency across scales and contexts of decision making. They may be the result of cultural or inherited traits.

Communication

The challenge of communicating uncertainties, assumptions and limitations, given that the choice of adaptive response is often controversial and liable to scrutiny is important to address. This includes the need to avoid over-technical approaches that might not fit well with some examples of risk, to explain constraints in order to avoid the development of unrealistic expectations around outcomes, to ensure the relevance of outcomes to decision makers (e.g. focussing on urgency, relating risks to current policy outcomes). The presentation of CCRAs can affect their effectiveness in stimulating change; examples from text were the assessment of risks associated with current policy, and how current objectives might be threatened by climate change, and the use of risk registers that use the dimensions of likelihood and impact to bring together, rank, highlight and communicate a range of risks. Transparency and close engagement with users of CCRA outputs are highlighted.

Data on adaptation (availability and quality)

The need to better incorporate into CCRA information on the viability of adaptation options, and on the way their effectiveness varies with different scenarios of future change (sensitivity in the context of uncertainty). Lack of data is an important limitation to CCRA, for example relating to monitoring or evaluation of adaptation options, to biophysical systems, their responses and the impacts of human actions on them, and on adaptive capacity. There is a need for improved data quality to move on from piecemeal and/or qualitative/subjective assessments (e.g. expert judgements or stakeholder exercises) to systemized data collection, appraisal and presentation. Monitoring and evaluation data are in many cases limited in terms of survey size and sample type (e.g. only early adopters). Consistency is needed in framing risks and uncertainties and the criteria on which adaptations are evaluated needs to be considered (see also under 'ethics'). Approaches have been developed and used to apply global data to more localised CCRA, to overcome some challenges relating to a lack of data.

Developing new CCRA methods

Risk registers can be useful but may become over-technical, leading to frames being fitted to risks that they are not suited to. In Italy the climate risk index improved model ensemble data and applied a more robust analysis to rank administrative areas in relation to different climate change impacts, in order to support the allocation of funds for adaptation. In CCRA methodological advances such as the business-function framework for business and industry risks are mentioned.

Diversity and number of factors

Diversity is present in i) the context of adaptation, including the perspectives of those involved, what they value or feel concerned about (different types of change and impact, different timescales of change), ii) the diversity of evidence types on which CCRAs must be based, iii) the different underlying assumptions, uses of scenarios and scope of CCRAs, iv) the diversity of risks and adaptive options which means that fitting risks into strict technical parameters for CCRA may not be appropriate. Large numbers of options are also likely to be available for adaptive change.

Ethics

Why intervention should take place and in what form, how CCRAs are presented (including scope, uncertainty, limitations, framing). Recognition of risk as subjective and perceived differently by different groups is mentioned, and aspects such as how adaptations are evaluated (e.g. effectiveness and fairness) are relevant.

Expectations

Decision makers are expecting more from CCRAs, including for example information on the adaptive impacts of current policies and assessments of how to make adaptations more effective. Some examples of CCRAs used in practical policy processes include the climate risk index for Italy which used detailed ensemble modelling and analysis to rank administrative areas according to the risks they faced in relation to specific climate change impacts. Outcomes informed the distribution of financial resources for adaptation. Those using CCRAs need to recognise that complete avoidance of risk is not likely to be practical. Engaging throughout the process of CCRA can help build understanding and reduce differences in expectation between those producing and using the CCRA.

Experience of decision makers

A challenge for climate change adaptation CCRA is that decision makers often have limited experience of dealing with problems with large numbers of alternative options and high uncertainty, while past experience of change often used to quantify risk in CCRAs is not adequate under climate change conditions.

Interdependence

Challenge to understanding i) how risks cascade through interdependent systems (biophysical and human) and ii) how adaptive actions on the ground, policy and risk levels interact. In relation to i) work is needed to better understand linkages and critical transitions within systems (including biophysical-human system interactions). Such interactions and the incorporation of multiple time scales are beyond conventional RA methods but need to be understood to address systemic risks. Using expert stakeholder knowledge can provide a route to understanding how risks are transmitted across sectors and scales. Risk transmission framing is mentioned as a specific methodological advance in relation to assessing cascading risks.

Interdisciplinary and trans-disciplinary approaches (collaboration)

Challenge of dealing with the wide and interacting impacts of climate change and adaptive responses, including the key integration of biophysical and socio-economic aspects of exposure and vulnerability, and the linking of disaster risk management and CC adaptation expertise. Challenges for research and decision makers at policy level can be addressed by considering the experiences of CCRA in specific sectors, and approaches used to address other complex issues can also be learned from. CCRA approaches for infrastructure and business risks are mentioned as methodological advances relating to specific sectors. Stakeholders can provide expert knowledge to complement scientific understanding. Links across disciplines need to be integrated with links to the needs of adaptation policymakers at a strategic level.

Interests

Individuals and groups vary in how they respond to risk and the types of risk and types of things affected are likely to be qualitatively different, so that attempts at ‘objective’ comparisons can lead to choices that are suboptimal in terms of people's needs (e.g. irreversible changes, value related to attachment to places and systems with cultural significance). The interests of some groups may trade-off with those of others, and may be sub-optimal when considered more broadly (e.g. policy drive to incentivise food production over environmental protection). Priorities may also link to deeper underlying values that may not be explicit. These issues create a challenge at points where objective CCRAs and subjective perspectives interact. Taken together, the issue of interests raises the important issue of who should be involved in determining the scope and nature of CCRA and the extent and type of response, given that those making choices may not wish to take precautions.

Scenarios

The interactions of climate change with global change in systems resulting from a variety of stressors is a big challenge for scenarios that will need to incorporate how different drivers of change co-evolve, for example by pooling data to discover confounding factors. Scenarios can be used to represent diverse pathways exceeding those accessible through conventional prediction, facilitating understanding of the consequences of change. Presenting a range of scenarios (including extremes) is also a strategy to deal with uncertainty in predictions (see 'Uncertainty').

Scope

The scope of an CCRA can affect how it is used and how risks are perceived, as well as affecting the accuracy with which incorporated risks are assessed. More recent CCRAs have incorporated socio-economic drivers of vulnerability and CCRAs are being widened to incorporate climate change opportunities to improve balance in decision making. There has been recognition of issues relating to impacts and adaptive responses that cross political borders (relates also to interdependence) and how these can affect risk and adaptive responses. Inclusion of the impact of current adaptation actions on future risk, from policy aspirations to action and adaptive capacity is important, including how different policy drivers might interact with adaptation needs to positively (or negatively) effect risk. Finally, a need to characterise risks and issues related to different coping potentials was identified. Scope interacts with expectations of what CCRAs should provide for policy makers, as well as what they incorporate into their conclusions, with an emphasis on the need to engage with policy and implementation in addition to publishing reports. The review also highlights a modelling challenge also raised by modellers – that the variety and diversity of adaptations is a challenge for integrated assessment models that do not incorporate all the required parameters or interactions.

Socio-economic drivers (data availability)

Incorporation of social and economic factors and their interaction with climate change and the nature of adaptive responses into CCRA, drawing on agent based modelling or qualitative understanding of human behaviour.

Time lags in adaptation

Implementation of change might not be instant, and may take some time for practical reasons or due to the existence of other barriers (institutions, social reasons) – these issues need to be incorporated in assessments of the extent to which an adaptation can offset climate related impacts.

Uncertainty

Uncertainty can limit action if adaptation is undertaken only in the light of predictions. However, predictability is suggested by some authors to be more important when there are few alternative options for action and relative certainty in outcomes – this is not the case with climate change. Uncertainty may relate to consequences or likelihood of climate change impacts or in relation to the effects of adaptive actions. In relation to climate change, much uncertainty is probably irreducible. Therefore, 'wait and see' is not a positive strategy. Some authors have suggested that uncertainty can be used as knowledge in itself, affecting how the viability of different options for change is viewed. Questions are raised about whether reducing uncertainty increases the effectiveness of decision making, although the importance of providing boundaries to potential outcomes are emphasized by some. Having a range of scenarios – including extremes – may assist decision making under uncertainty and being explicit about the goals of adaptation is also important. Involving stakeholders in participatory approaches to change based on precautionary principles can be a more effective path for decision making with unavoidable uncertainty than using metrices and making decision trees. Other approaches include incorporating the temporal aspects of change (e.g. dynamic adaptation pathways with trigger points, robust decision making approaches, and risk layering according to risk and return periods) and stress testing to assess critical levels for ecosystem functioning in natural systems.

D2. Comparison with reviews

A summary of the comparison of workshop findings with themes drawn from Adger et al. (2018) and with challenges to grassland modelling and to livestock health and disease modelling under climate change (CC) is shown in Table D.1.

Table D.1
comparison of agricultural adaptation modelling challenge themes, themes drawn from Adger et al. (2018) (See S2.1 for description of themes), CC adaptation challenges previously identified for grassland and for animal health modellers, and broader climate-related challenges identified for these modelling disciplines. The Adger et al. (2018) theme 'Developing new CCRA methods' is not included in the table as it would associate with all themes within the 'Capacity' category in the current study.

Category (current study)	Theme (current study)	Themes from Adger et al. (2018)	Grassland modelling (adaptation specific)	Grassland modelling (general climate change)	Animal health & disease modelling (adaptation specific)	Animal health & disease modelling (general climate change)
Capacity	Collaboration	Inter-disciplinary and trans-disciplinary approaches		Links to other disciplines to explore impacts of changes in grasslands on the nutritional value of the sward for animals, & on the economics of systems; Fit-for-purpose models (use of model platforms & modular approaches for model integration)	Links to other disciplines to understand health interactions with other aspects of production; improved regional economic modelling of CC & socio-economic impacts of health changes & adaptive responses	Terminology and measurements: differences in international and interdisciplinary collaboration; Fit-for-purpose models (use of model platforms and modular approaches for model integration)
	Data availability	Data on adaptations (availability and quality); Socio-	Collation of data on adaptation strategy, their efficacy and impacts	Data for models (including availability, accessibility,	Data on costs and efficacy of both health issues & interventions	Implicit in other challenges, e.g. need for data on different systems, on

(*continued on next page*)

Table D.1 (*continued*)

Category (current study)	Theme (current study)	Themes from Adger et al. (2018)	Grassland modelling (adaptation specific)	Grassland modelling (general climate change)	Animal health & disease modelling (adaptation specific)	Animal health & disease modelling (general climate change)
		economic drivers (data availability); Biophysical knowledge (data availability)		quality); fitting model & data scale		pathogen, pest & host ecology, at different scales & in relation to model scope
	Data quality					Need for data collection protocols, agreed standards, approaches and terminology
	Data accessibility	DATA ACCESSIBILITY NOT MENTIONED			Collating adaptation options related to different health conditions	Issues relating to data ownership and sharing in a competitive context
	Novel scenarios	Scenarios	Context specific adaptation scenarios based on stakeholder needs		Creating adaptation scenarios	
	Resources for modellers	RESOURCE LIMITS NOT MENTIONED				
	Uncertainty	Uncertainty	Implicit across challenges in terms of need to improve data and modelling capacity	Implicit across challenges in terms of need to improve data & modelling capacity & adequacy for stakeholder requirements – including using ensemble modelling approaches	Ability to model a range of climate change scenarios and the robustness of adaptive solutions across these; uncertainty in uptake likelihood for adaptation strategies	Implicit across challenges in terms of need to improve data and modelling capacity and adequacy for stakeholder needs/expectations, including accuracy
Content	Discrete events modelling	Mentioned only in relation to collaboration with disaster risk management research		Modelling the impact of extreme events		
	Dynamic change modelling	Interdependence; Time lags in adaptation	Dynamics of uptake and implementation, threshold changes and carry-over effects		Incorporating implementation of adaptations over time	Pathogen and vector spread
	External limitations modelling	Interdependence; Scope		Implicit in need to extend model scope and to link models of different types		Implicit in need to extend model scope and to link models of different types
	Interactions modelling	Interdependence	Management driven by/a driver of biophysical change; Interactions between management changes and other systemic processes, & between different management changes	Modelling livestock & pasture interactions; Modelling plant responses to environmental change	Capturing farm and policy level strategies and their impacts; Improved modelling of environmental impacts on health, and of the biophysical processes via which adaptations cause change	Impacts of climate on health; Impacts of health on GHG emissions; Impacts of health on production; Interactions between health conditions, pathogens and interventions
	Management modelling	Cognitive bias	Inclusion of realistic decision making			
	Scale interactions	Interdependence		Model & data scales – model linking, scaling data etc.		Modelling across spatial & temporal scales
	Scope	Scope; Diversity and number of factors	Novel adaptations (e.g. novel breeds) and systems (e.g. silvopasture)	Modelling different regions & production systems (to assess CC impacts); Challenges on incorporating into models (nutrient balances, GHGs, ecosystem services, soil variables & processes, pests & pathogens, overwintering, multi-species swards, nutritional variables)	Capturing farm and policy level strategies and their impacts	Variation in capacity between systems and nations; Nutrition and health; Pathogen, vector and host ecology; Genetics of health; Land use change and health
Use	Communication	Communication; Ethics; Expectations; Experience of decision makers; Interests		Fit-for-purpose modelling – engaging stakeholders to improve model relevance and understanding		Fit-for-purpose modelling – engaging stakeholders to improve model relevance and understanding
	Engagement approach			Fit-for-purpose models: Information on models and their capabilities made easily available for stakeholders, including limitations		Stakeholder involvement – to gain local info of disease patterns, & build trust & relevance through engaging in model development; Fit-for-purpose models: Info on models & their capabilities made easily available for stakeholders, inc. limitations
	Role of modellers					
	User focus		Included in the need for context specific scenarios relevant to stakeholders	Making models fit-for-purpose in relation to stakeholder needs	Improved evaluation of model assumptions and performance, particularly for empirical models	Fit-for-purpose modelling meeting stakeholder needs; Validation of empirical relationships under CC

Appendix E. Illustrative reviews of modelling climate change adaptation

Three mini reviews explore how agricultural modellers are tackling specific challenges to CC adaptation modelling (main paper Fig. 2). The first considers how modellers work with stakeholders (main paper Fig. 2, A, D), and the remaining two focus on 'Content of models' challenges (main paper Fig. 2B and C) and cover bio-economic modelling and biophysical modelling. Collaboration (main paper Fig. 2, E) is covered in the main text.

1. Climate change adaptation modelling and stakeholders

Responsibilities of modelling under progressive change

Recent integrated modelling initiatives have demonstrated the use of agricultural modelling within a process in which model outcomes provide the basis for exploring the broader impacts of change, beyond those normally incorporated in agricultural modelling. In Sardinia models revealed likely reductions in summer sheep's milk production under CC; considering this, researchers and stakeholders explored potential consequences for the supply chain and other economic sectors (Dono et al., 2016). Lower milk production would reduce availability of cheese for tourists, while reduction in milk quality could cause problems for transformation into products with a quality label. One issue exemplified by this study, is that of limitations and uncertainty in modelling. Available statistical heat stress models were not able to incorporate adaptive responses, demonstrating the importance of clearly communicating the meaning and limitations of results to avoid misuse. Such limitations include uncertainty about CC impacts and adaptive responses. The use of impact (Pirttioja et al., 2015) and adaptation response surfaces (Ruiz-Ramos et al., 2018) together with robustness indexes of adaptation recommendations (Rodríguez et al., 2018) have been used in biophysical models to address this challenge. Uncertainty makes developing sound protocols for adaptation modelling vital in preventing model misuse and reducing the potential for incorrect or misinterpreted outputs to drive mal-adaptive change (Ramirez-Villegas et al., 2015).

A second issue raised within the Sardinian study, was that dairy cow systems with access to irrigation were predicted to be less affected by CC than more traditional sheep systems. Choices made by policymakers presented with such evidence, would depend on how the modelling message was framed, and what was valued in that framing (e.g. economic benefit, ecological footprint, tradition and culture, tourism or agriculture, the interests of a particular sector). Modelled impacts might therefore drive adaptive responses in very different directions, changing who is affected by climate change, and how (Reckien et al., 2017). In undertaking and presenting findings modellers may unwittingly be used to support the case of specific stakeholder groups (Lang et al., 2012). In highlighting how models can shape stakeholder views and agendas, the data from this study illustrate how modellers might alter what stakeholders consider in their choices. This issue might be addressed by considering how to make researchers more accountable for their influence on decision-making, or by ensuring that, by representing the agendas of the affected as well as the affecting, and by expressing the limitations to their work, modellers can enable stakeholders and policymakers to retain responsibility for their actions.

The progressive nature of CC and (as a result) CC adaptation, and how it shapes the systems on which humanity relies, brings to the fore the tension between research following pragmatic, consensus-seeking approaches to engagement, and critical approaches that see exploring and making different societal groups aware of conflicts and power relations as prerequisites for just solutions (Johansson and Lindhult, 2008). While social learning approaches facilitating co-learning between researchers and stakeholders may underpin more effective, sustainable, bottom-up change in agriculture (Nguyen et al., 2014) questions still remain about how the needs and values of those outside the process are recognised. The ability of modelling to help stakeholders understand how their actions can affect other systems and actors (Martin et al., 2011; Vieira Pak and Castillo Brieva, 2010) suggests a role in helping stakeholders and policymakers at all levels to conceptualise the types of CC futures their adaptive choices are likely to create. How well modellers can fulfil the role of facilitating learning and exploration by stakeholders, is linked to the extent to which they are willing and can work together across disciplines to recognise and present a range of strategies and consequences.

Information on adaptive responses to progressive change

For models such as regional Integrated Land use Models (ILMs) or biophysical models well-specified adaptation strategies may be included as inputs – these are frequently defined by experts. External information can be added about the adaptation (e.g. for ILMs, the regional availability of relevant technology, and the required infrastructure and conditions, such as water availability and institutional settings). Although technical coefficient generators can be used to identify a large range of alternative adaptations; e.g. Janssen et al. (2010), information may also be needed on adoption (e.g. in positive mathematical programming models) posing a particular challenge for adaptation measures which are not yet available. At regional level, socio-economic scenarios are being created to consistently define framework conditions for adaptation, improving transparency and comparability in the assumptions underlying model predictions. These include the Regional Agricultural Pathways (RAPs) developed within AgMIP (Valdivia et al., 2013). RAPs are characterised with input from stakeholders and experts to ensure their coherence and relevance. However, scenarios may still face issues including limitations in the scenario-building approach, the choice of stakeholders and experts from whom to gather data, and the potential for uncritical inclusion of implicit sociological assumptions (Jansen, 2009).

At farm-scale, eliciting farmers' objectives is not straightforward; what they say and what they do may not be the same (Mandryk et al., 2014). Rather than using expert judgement to validate the performance of decision making sub-models, models such as MELODIE (Chardon et al., 2012) have used on-farm observations of real behaviour (Chardon et al., 2008; Garcia et al., 2005) removing doubt about the accuracy of reported actions. However, validation based on observed behaviour may not reflect future choices under progressive CC. In addition, lack of knowledge about the future availability and quality of alternative inputs (e.g. concentrate feeds) may limit the ability of modelling at farm-scale to apply relevant scenarios. Studies using the bio-economic farm-scale model FSSIM (Kanellopoulos et al., 2014; Wolf et al., 2015) came to different conclusions due to differences in the projected possibility of renting land, which influenced crop rotations, constraining choices.

A range of approaches exist for increasing the accuracy of predicted behaviour in farm-scale bio-economic modelling (Reidsma et al., 2018). Some maintain assumptions of rational, profit maximising behaviour, but include impacts of uncertainty and changing experience in decision making processes, such as the use of Discrete stochastic programming (Dono et al., 2016), or make alternative assumptions about farmers' risk behaviour (Finger and Calanca, 2011). Forming links between agricultural modellers and Agent Based modellers (Berger and Troost, 2014) including those focussing specifically on modelling human adaptive behaviour under global environmental change (Acosta-Michlik and Espaldon, 2008; Acosta-Michlik et al., 2014) offers the potential to explore ways to use their modelling to provide improved adaptation scenarios, or to more realistically represent adaptive behaviour endogenously.

Given the unavoidability of uncertainty about future choices, one approach is to produce a range of outcomes based on different scenarios and adaptation choices which stakeholders can subsequently discuss, rather than ranking outcomes to suggest a recommended 'best' action (Dittrich et al., 2017; Mandryk et al., 2014). Model findings may also be presented in the context of a critical assessment of wider implications of implementation including adaptation effects on social or environmental objectives such farm income, CC mitigation, or water quality; e.g. Reidsma et al. (2015a,b), Schönhart et al. (2018). They become one among a range of inputs to a broader process of social learning in which stakeholders, together with researchers from different disciplines, develop a shared understanding of problems and solutions (Nguyen et al., 2014). This feeds into the idea of cycling between biophysical and socio-economic aspects in participatory processes of research, and the creation of adaptive loops to maintain flexibility in the face of changing conditions (Howden et al., 2007). A recent review of scenario planning (Star et al., 2016), provided a matrix of approaches that can be aligned with different roles for modelling, which may: support stakeholders in determining adaptation strategies that help them meet the (normative) objectives they desire, provide a range of (exploratory) outcomes for them to consider, present them with a recommended (normative) outcome, or finally, provide a range of strategies that they would like models to explore. Engagement with experts in scenario planning can therefore address issues relating to gathering information on future conditions, with different approaches supporting modellers in tackling the challenge of Responsibilities of modelling in the context of progressive change (Fig. 1, A).

2. Bio-economic modelling

Scope of adaptations modelled

To characterise how adaptation affects biophysical processes, farm-scale bio-economic models rely on either, inputs from biophysical models (from one-off data input to integrated frameworks) or the creation of simpler endogenous representations of biophysical systems. The scope of adaptation strategies they characterise is therefore constrained by the scope of these linked models, including in relation to the objectives of adaptation strategies, with most crop models focussing on yield rather than other types of outcome (Mandryk et al., 2014, 2017). Linking to crop models using modular approaches is a common solution to increase scope, e.g. the link between EPIC and FAMOS[space] (Schönhart et al., 2016), or WOFOST and the Agro Climate Calendar and FarmDESIGN (Mandryk et al., 2017), where crop management choices are modelled at field level.

Fewer models link to biophysical animal models, with livestock production often represented via feed budgeting and/or herd dynamics modules (e.g. FAMOS[space], ScotFarm, MODAM) with annual or monthly time steps. Farm-scale bio-economic models might also include integrated cropping or soil processes, exemplified by the incorporation of soil carbon stocks in FarmDesign (Groot et al., 2012). Adaptation modelling is then possible to the extent that CC and adaptation impacts can be translated to the relevant co-efficients in these modules (e.g. change in milk yield or liveweight gain). Solutions for fully integrated livestock and crop production sub-modules also exist; for example, the DairyNZ model takes weather data directly, with pasture and cow metabolism modules operating with a daily time step, and an annual time-step economic module (Kalaugher et al., 2017).

At regional level, ILMs have a wide spatial scope from landscape (Briner et al., 2012; Reidsma et al., 2015a,b) and sub-regional (Schönhart et al., 2014) to continental levels (Holman et al., 2017) and integrate field, animal, and farm-scale biophysical and economic models (or components of them) to represent bio-physical and human systems and their interactions. Regional ILMs based on a normative concept of adaptive decision making, such as some linear programming models assuming profit maximization (Annetts and Audsley, 2002; Kirchner et al., 2016) have the scope to model novel land use outcomes (e.g. new crop species or the adoption of new technology) although this requires prior specification of the measure by the user – this is particularly challenging in regional ILM due to their large spatial and farming system coverage. Regional ILM based on positive concepts of adaptation decision making, such as positive mathematical programming (PMP) models (Schönhart et al., 2014) or econometric models (Fezzi and Bateman, 2015; Moore and Lobell, 2014) may face challenges in representing adaptation beyond previously observed ranges. An option to overcome this limitation is the incorporation of observed management practices from other regions, where climatic conditions are similar to those expected in the focus region under CC. In terms of representing future technologies, Dietrich et al. (2014) endogenously modelled investment-dependent technological change in the global ILM MAgPIE. For ILMs, further research is required to understand adaptation outcomes when relationships between farms, supply chains, and marketing of agricultural products are taken into account.

Optimisation under progressive change and with thresholds

Dynamic bio-economic farm-scale models such as ScotFarm can represent inter-temporal dependencies (e.g. agronomic effects of adaptation via changing rotations or herd management or the financial aspects of longer term investment and policy and/or market changes). Agronomic thresholds can be incorporated into farm-scale bio-economic models either via the functions of specific modules (e.g. linked crop models) or external data input. However, incremental adaptation can only be assessed if relevant processes are integrated or if data are provided from external models (Janssen et al., 2010; Schaap et al., 2013). Economic thresholds (e.g. farms going out of production due to losses) can be represented, although financial modules often work at the gross or net margin level, not considering reserves and credit availability. To the extent that alternative practices can be characterised, step changes in management and in contextual scenarios can be compared, including the impacts of long-term financial investment (which can be annualised over the investment's lifetime to make them comparable).

While some adaptation requires binary decisions (e.g. whether to establish cover crops on a plot), other decisions can be continuous (e.g. the choice of fertilisation levels or irrigation rates). ILMs frequently link single models sequentially and are static with respect to land use decisions, rarely representing feedbacks of adaptation choices on CC altered biophysical systems. Consequently, they are limited in relation to evaluating how the costs and benefits of adaptation strategies evolve over time. Modelling of dynamic adaptation processes such as applied in bio-economic farm models is complicated by the larger spatial and farming system coverage of ILMs. Even for market feedbacks, many applications use exogenous price assumptions on agricultural inputs and outputs independent from adaptation choices. In regional ILMs, adaptation thresholds are mainly determined by economic cost-benefit considerations – a considerable simplification from real-world decision making. One-off investment decisions can be modelled by comparing average costs and benefits (e.g. represented in annuities) but this requires assumptions about the dynamic effects of adaptation strategies such as transition periods. Options to overcome challenges relating to optimisation under progressive change include risk sensitive dynamic modelling of annual land use decisions (Lehtonen, 2012). Abstracting from the farm level in regional ILM eases the representation of transformative shifts between farming systems, such as land cover conversion, changes in livestock, or between organic and conventional farming systems. However, static models are prone to overestimating the likelihood of dynamic transformation processes (e.g. forest succession); including risk behaviour, as in many bio-economic farm models (Liu et al., 2016), can make such the representation of adaptation choices more realistic.

3. Biophysical modelling

Scope of adaptations modelled

The focus of many recent crop model inter-comparisons has been on wheat e.g. Asseng et al. (2013), Martre et al. (2015) maize and rice (Ehrhardt et al., 2018) and Rötter et al. (2018) have highlighted the need to widen the focus of modelling to cover more systems, including tropical crop production. The effects of CC on pest and disease ecology and spread, and the consequences for different plant species and communities also need to be better incorporated into models as a pre-requisite to simulating the impacts of adaptation strategies focussed on plant health (Newbery et al., 2016). Challenges of model scope and adaptation impact are being tackled in relation to several specific adaptations, including modelling crop rotations (Kollas et al., 2015) and CC effects on harvest quality (Nuttall et al., 2017; Wheeler and Reynolds, 2013). The characterisation of inter-cropping systems and crop mixtures is also challenging with most models currently representing such systems as a single crop, with characteristics based on those of the combined crop. An advance is the characterisation of two species independently, accounting for soil nutrient and light sharing between them, e.g. STICS, Corre-Hellou et al. (2009). Multi-species grasslands are also likely to be more resilient to CC (Tilman and Downing, 1994; Tilman et al., 2006). Taken together the need for multi-species modelling for arable and grassland systems creates potential for collaboration with ecological modellers more used to dealing with multi-species swards (Kipling et al., 2016, Van Oijen et al., 2018). Recent work in this area includes the development of dynamic modelling of both species composition and changes in biomass in productive grasslands (Moulin et al., 2018). Grassland models have flexibility through their mechanistic incorporation of a range of biophysical processes, such as plant-grazing animal interactions (Graux et al., 2011). The inclusion of these and other detailed sward processes, along with outputs relating to production, nutrient flows and GHG emissions (Sanz-Cobena et al., 2017), demonstrate the scope of such models to characterise adaptive changes via the alteration of input variables by the user.

As in the case of bio-economic models (section 3.4.2) the scope of farm-scale biophysical models to characterise novel adaptations, is determined by the capabilities of the crop and grass models to which they are linked. Thus, in MELODIE (Chardon et al., 2012) a dynamic model designed to simulate nutrient flows across a mixed farming system, operational (short term, within a season) adaptations associated with crop and grassland management and short term changes in feed rations are incorporated via the STICS crop model. Tactical (annual) adaptations linked with the planning of crop rotations, feed rations, and fertilisation strategy are also simulated using specific sub-models (Chardon, 2008; Chardon et al., 2008). However, farm scale models must also consider adaptations associated with farm infrastructure and resources (e.g. housing, imported feed) and interactions between these systemic components that might produce emergent effects (Chardon et al., 2012). Within MELODIE, manpower, machinery and some aspects of animal housing (e.g. control of ventilation, alleviation of heat stress or addition of water to slurry tank) are not included, excluding consideration of related adaptation strategies. Assessing the value of some tactical adaptations like the use of cover crops, changing crop species/varieties, or the implementation of different tillage practices is possible, but only by comparing several (with vs without adaptation) scenarios, and not by simulating such changes in response to external factors. Similarly, some adaptations can be simulated by altering input variables (e.g. change in the calving pattern, use of alternative forages, changes of breeds or changes in manure processing). Inclusion of farm-scale biophysical models in modelling platforms, e.g. MELODIE within the INRA modelling platform (Bergez et al., 2013) allow them to benefit from improvements in sub-models. Modular structures for farm-scale models offer an important technical solution to the challenge of characterising a wider scope of novel CC adaptations in both biophysical and bio-economic modelling (Janssen et al., 2010).

Optimisation under progressive change and with thresholds

Many crop models are only designed for single season runs (Rötter et al., 2018), making it hard to consider the relative outcomes of adaptation strategies over different time scales. A major challenge is the development of approaches to incorporate carry over effects of management change, for example progressive shifts in sowing dates and how performance in crop rotations alters according to the effects of previous crops in the rotation (Pappa et al., 2012); without characterising these effects, adaptation under progressive CC cannot be fully assessed. Similarly, in grassland modelling capturing dynamic change in swards under progressive CC (Kipling et al., 2016) is a prerequisite to fully assessing the cost-benefits of adaptation strategies over different time frames.

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