Key challenges and priorities for modelling European grasslands under climate change

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Abstract

Grassland-based ruminant production systems are integral to sustainable food production in Europe, converting plant materials indigestible to humans into nutritious food, while providing a range of environmental and cultural benefits. Climate change poses significant challenges for such systems, their productivity and the wider benefits they supply. In this context, grassland models have an important role in predicting and understanding the impacts of climate change on grassland systems, and assessing the efficacy of potential adaptation and mitigation strategies. In order to identify the key challenges for European grassland modelling under climate change, modellers and researchers from across Europe were consulted via workshop and questionnaire. Participants identified fifteen challenges and considered the current state of modelling and priorities for future research in relation to each. A review of literature was undertaken to corroborate and enrich the information provided during the horizon scanning activities. Challenges were in four categories relating to: 1) the direct and indirect effects of climate change on the sward 2) climate change effects on grassland systems outputs 3) mediation of climate change impacts by site, system and management and 4) cross-cutting methodological issues. While research priorities differed between challenges, an underlying theme was the need for accessible, shared inventories of models, approaches and data, as a resource for stakeholders and to stimulate new research. Developing grassland models to effectively support efforts to tackle climate change impacts, while increasing productivity and enhancing ecosystem services, will require engagement with stakeholders and policy-makers, as well as modellers and experimental researchers across many disciplines. The challenges and priorities identified are intended to be a resource 1) for grassland modellers and experimental researchers, to stimulate the development of new research directions and collaborative opportunities, and 2) for policy-makers involved in shaping the research agenda for European grassland modelling under climate change.

Keywords

Climate change; grasslands; horizon scanning; livestock production; models; research agenda

1. Introduction

The agricultural sector is facing unprecedented challenges as it attempts to maintain food security in the context of climate and socio-economic change (Soussana, 2014; Thornton, 2010). The forecasted increase of world population, dietary changes towards increasing meat consumption and the demand for bioenergy suggest a global requirement for agricultural products by 2050 roughly twice that of today (Foley et al., 2011). At the same time as increasing production, the livestock sector will need to improve efficiency (Thornton, 2010) to avoid increasing the 26% of global land area currently used for livestock production, and to reduce its estimated 15% share of total anthropogenic greenhouse gas (GHG) emissions (Ripple et al., 2014). Havlik et al. (2014) suggest that transitions from grass-based to more intensive livestock production systems may represent a cost-effective approach to mitigating GHG emissions from livestock agriculture. However, while grass-based ruminant production systems may be less efficient in terms of GHG emissions and land use than more intensive systems, they provide a range of other benefits; European grasslands store an estimated 5.5 Gt of carbon in the top 30 cm of their soils (Lugato et al., 2014). Covering around 30% of agricultural land in Europe (Huyghe et al., 2014), grasslands also play an important role in the maintenance of biodiversity and the sustenance of rural communities and cultures (Soussana and Lemaire, 2014). Intensification or conversion of grasslands to crop production can lead to the reduction or loss of such benefits (Dusseux et al., 2015). At the same time, ruminants valorise marginal production areas, converting plant materials indigestible to humans into meat and dairy products with high efficiency in terms of the consumption of human-edible food per unit of product (Wheeler and Reynolds, 2013; Wilkinson, 2011). In Europe, around 25% of livestock protein intake comes from grasslands (Leip et al., 2011). Despite these benefits, grasslands have declined in Europe, with an estimated loss of seven million hectares between 1967 and 2007 (Huyghe et al., 2014). Recent predictions suggest that this decline may continue in a climate change future (Leclère et al., 2013). In this context, a better understanding is required of the impacts of climate change on European grassland systems, the efficacy of adaptation strategies to increase their resilience and productivity, and the pathways available to maintain and enhance the essential ecosystem services they provide (Scollan et al., 2010; Smith et al., 2013).

In light of the challenges described, modelling can offer valuable support to farm and policy level decision-makers, by providing tools to explore the performance of biophysical, management and policy systems in the context of future climatic and socio-economic scenarios (Graux et al., 2013; Kipling et al., 2014). A number of high-level strategic assessments of agricultural research priorities (ATF, 2013; 2014; FACCE-JPI, 2012; Soussana, 2014) present a range of challenges to the agricultural modelling community (Kipling et al., Accepted). The aim of this paper is to lay out in detail the specific challenges and research priorities that grassland modelling must address, if it is to fulfil its potential role in helping to tackle the global problems faced by the livestock production sector. The focus of the paper is on European grasslands, and covers both permanent grasslands and leys (grasslands established for less than five years). Three broad types of model applied to European grasslands have previously been identified (Bellocchi et al., 2013); specialised grassland models, crop models with grassland options, and vegetation models that can characterise a range of plant communities including grasslands. This paper incorporates challenges relevant for all of these model types, and explores links to other modelling disciplines and approaches.

2. Methods

In order to understand the challenges and research priorities for grassland modelling, a 'horizon scanning' approach based on that of Pretty et al. (2010) was used to gain the views of grassland modellers and researchers from 18 institutes across 10 countries. The experts were drawn from, or known to, partners contributing to a large European modelling network, the Agriculture, Food Security and Climate Change Joint Programming Initiative (FACCE JPI) knowledge hub Modelling European Agriculture with Climate Change for Food Security (MACSUR) (http://www.macsur.eu). Views were gathered using a workshop and questionnaire and corroborated through the literature, with the scope of discussions determined through a pre-workshop mapping process.

2.1. Mapping Process

Grassland models can cover a range of systems and processes, and a scoping exercise was necessary to define the boundaries for discussions and questionnaire responses. Workshop facilitators and task leaders involved in relevant activities within the MACSUR project created a single page diagram intended to capture the components, processes and interactions associated with grassland modelling. Participants were then asked to comment on and amend the map in an iterative process, until a consensus was reached. The final map (Fig. 1) was used as a reference in workshop discussions and distributed along with the questionnaire to guide responses.

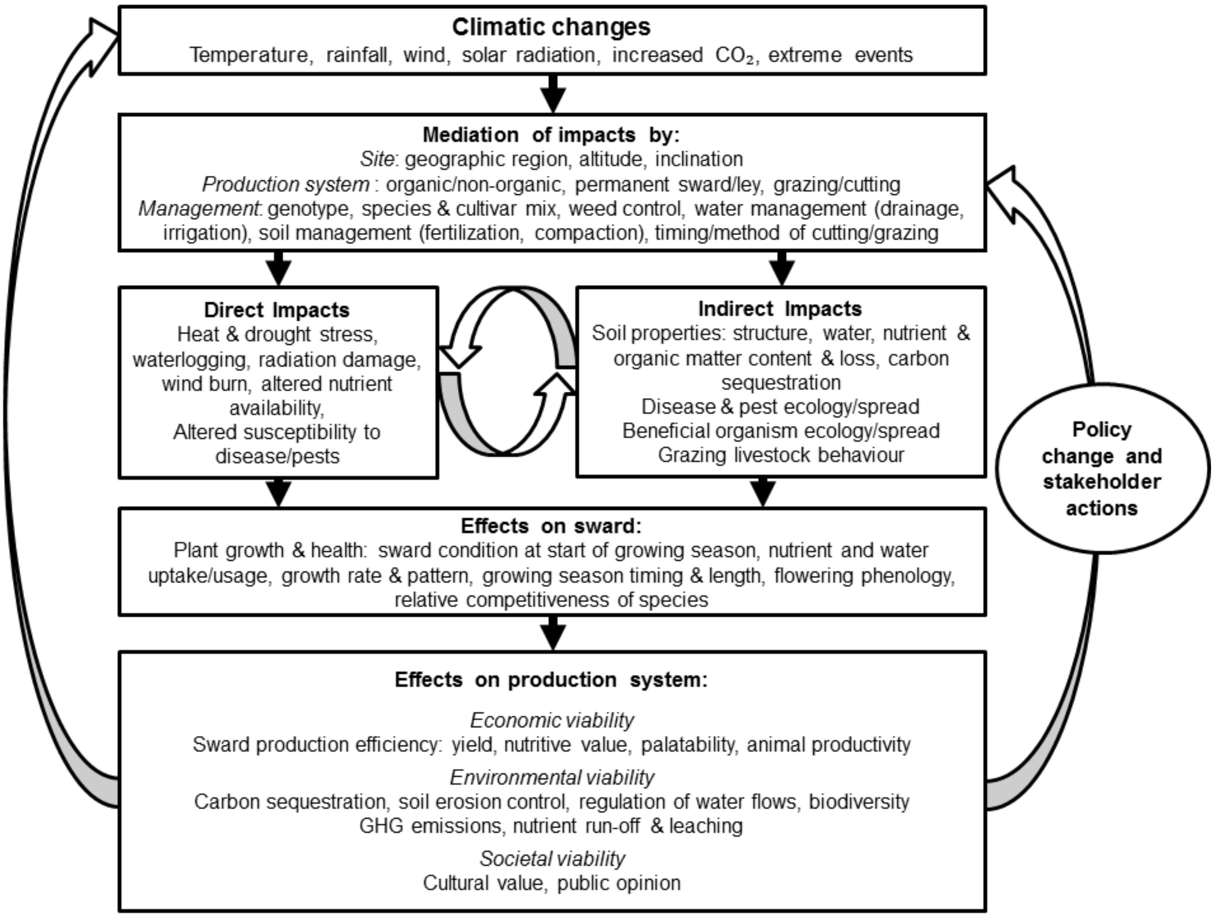

Figure 1: Map of impacts of climate change on grassland systems, including feedbacks.

2.2. Workshop Approach

A workshop was held between the 17th and 19th of June 2015 at Wageningen University and Research Centre (The Netherlands). Workshop sessions were organised based on the 'Futures Workshop' approach (Jungk and Müllert, 1987; Valqui Vidal, 2005) as adapted for use in the EU FP7 SOLID (Sustainable Organic and Low Input Dairying) project (http://www.solidairy.eu) . Workshop participants were divided into small groups (5-6 people) and were invited to identify challenges to modelling in the subject areas covered by the workshop. Each participant wrote down as many challenges as they wished. Asking contributors to write down their suggestions ensured that all views were taken into account, reducing the problem of bias towards the opinions of the most vocal participants, which has been recognised in some focus group settings (Kitzinger, 1995). In discussion with their group, facilitators brought similar challenges together to remove duplication, and arranged them logically according to identified links between topics. Secondly, groups identified the 'ideal world' that would exist if each individual challenge were overcome. In the third step, participants were asked to discuss the current position and the potential for moving towards the ideal state for each challenge. Participants then identified practical research steps that could be taken in each case. Finally, the small groups were brought together to exchange views and add further comments and thoughts to the 'maps' created. The approach enabled a structured set of challenges, research priorities and ideal world conditions to emerge from discussions of complex topics encompassing many different disciplines and viewpoints.

2.3. Questionnaire approach and synthesis of outputs

In order that views could be gathered from experts who could not attend the workshop, a questionnaire was designed using a similar structure to the workshop exercises and distributed to contributors (Appendix 1). The questionnaire asked respondents to list challenges to modelling, ideal states and the research steps required to move towards those ideals. Workshop outputs and questionnaire responses were combined in a single spreadsheet, removing duplicated challenges while retaining all distinct research steps identified. Information was shared with participants to provide another opportunity for them to add to the challenges and research steps defined, based on 1) the development of their thoughts following initial participation, and 2) consideration of their workshop and questionnaire responses in the context of existing literature. This round of revision enabled descriptions of the current state of research to be enriched with reference to existing review and research papers. The final list of challenges, ideal states and research steps were then grouped into overarching themes.

3. Challenges and priorities for modelling

The workshop and questionnaire responses identified fifteen challenges. Twelve of these could be categorized using the different aspects of grassland systems under climate change depicted in Fig. 1, and three were cross-cutting challenges (Table 1). The first category of challenges relate to 'direct and indirect climate change effects on the sward'. Challenges one to three refer to biophysical interactions which will require improved modelling in the context of climate change. These are followed by three challenges (four to six) relating to modelling plant responses to climatic change, while challenge seven considers the importance of widening the scope of modelling to take account of pests and pathogens, the impact of which is likely to alter as the environment changes. The category 'Climate change effects on grassland system outputs' (challenges eight to 10) focuses on how environmental changes affect the economic and environmental outputs of grassland systems. Challenges 11 to 12 in the category 'Mediation of climate change impacts by site, system and management' cut across individual biophysical aspects, and are related to increasing capacity in modelling different and changing systems, regions and management regimes. Finally, challenges 13 to 15 underpin the others, centring on making models that can adapt to stakeholder demands and overcoming technical and data-related challenges. These groups of challenges and priorities are described in the following section. The main lessons drawn from the challenges are then brought together (section 4).

Table 1: Challenges for grassland modelling identified by experts. Except for the methodological challenges, categories map onto the aspects of grassland systems depicted in Fig. 1. Challenges numbered as in the text.

Category	Challenge
Direct and indirect effects of climate change on the sward	**1** Modelling multi-species swards **2** Modelling soil variables/processes **3** Modelling livestock and pasture interactions **4** Modelling plant responses to environmental change **5** Modelling overwintering **6** Modelling the impact of extreme events **7** Incorporating plant pests & pathogens into models
Climate change effects on grassland system outputs	**8** Modelling the provision of ecosystem services **9** Modelling nutrient cycles and GHG balances **10** Modelling nutritional variables required to predict animal performance
Mediation of climate change impacts by site, system & management	**11** Modelling different regions and production systems **12** Modelling adaptation strategies
Cross-cutting methodological challenges	**13** Making models 'fit-for-purpose' **14** Linking different scales of modeling and data **15** Providing data for models

3.1. Direct and indirect effects of climate change on the sward

1. Modelling multi-species swards

The challenge: Species-diverse swards may improve grassland resilience to changing climatic conditions (MacDougall et al., 2013). However, biodiversity, which has been linked to the provision of ecosystem services, may be affected by climate change, as relationships (both competitive and mutualistic) between species alter in novel and more variable conditions (Tylianakis et al., 2008; Vicca et al., 2006). Many grassland models were designed for application to single species swards, or to simple mixes such as clover and ryegrass (Lazzarotto et al., 2009). As a result, they are often limited in their capacity to characterise interactions in multi-species swards. These types of interaction may be complex, including above and below ground processes (Blomqvist et al., 2000; Dhamala et al., 2015) and transfers of nitrogen from legumes to other species (Nyfeler et al., 2011; Pirhofer-Walzl et al., 2011). There is growing recognition of the importance of understanding better the role of groups such as legumes in mixed swards, with a need for high protein forages to reduce reliance on expensive supplementary feeds and reduce nitrogen inputs (Lüscher et al., 2014; Suter et al., 2015).

Some current process based models incorporate species mixtures to some extent (Ma et al., 2015) but further development is needed for uses that require characterisation beyond the definition of an average vegetation, for example in relation to the simulation of changes in sward composition. Snow et al. (2014) considered the ability of six grassland models to characterise multi-species swards, finding a diverse range of approaches to this challenge. They highlighted potential limitations in modelling more diverse swards, in the capacity of simpler approaches to adequately represent the impacts of changed conditions, and in the capacity to model novel species mixtures, such as swards including tree and shrub species. In the context of climate change, improving modelling capability in these respects is of particular importance, because of the expected changes in environmental conditions, increases in extreme events (challenge 6) and adaptation strategies incorporating increased sward diversity and agro-forestry (challenge 12).

Research priorities: A full review of current modelling capability, data and knowledge relating to multi-species grasslands is required as a first step in defining the options for developing modelling capacity, including a theoretical framework for new multi-species models. Outputs and approaches from the vegetation modelling community can provide important insights with respect to interactions between species or functional types and their responses to climate change (Scheiter et al., 2013). An exploration of work on plant functional groups to identify the most important traits and processes (parameters) for modelling would ideally be a part of such a review. The most important types of sward for modellers to focus on could be investigated by reviewing information on the species mixtures that (based on current knowledge) are believed to perform best under climate change. Through the development of modular modelling approaches (challenge 13) connecting biodiversity modules to existing models offers one potential route to improve modelling capacity in relation to multi-species swards (challenge 8). Inventories of grassland models have been compiled as part of the activities of current research networks such as MACSUR (Bellocchi et al., 2013) and comparisons of models such as that undertaken by Snow et al. (2014) provide the basis for a more systematic synthesis of information about current models. Online repositories such as the Agricultural Modelling Knowledge Hub (AgriMod) (http://agrimod.basedev.co.uk) can be used to share such information, allowing model developers to update entries as their models are improved over time.

2. Modelling soil variables/processes

The challenge: Many grassland models include fairly sophisticated ways of representing physical, chemical and biological soil processes (Bellocchi et al., 2013). However, a range of complex processes occur within the soil across many variables, including soil capillarity, leaching, evaporation, effects of soil biota (such as earthworms), changes in the seed bank, soil microbial activity, impacts of manuring and other fertilisation, and changes in soil organic matter. In the context of climate change, experimental research and modelling has often focussed on the impacts of individual variables affecting soil processes (soil warming, nitrogen deposition, water availability, CO_2 fertilization and fire) whilst it is known that interactions between such variables mean that their combined effects are not easily predictable (Sierra et al., 2015). There are also complex interactions between plants, mesofauna (Rossetti et al., 2015) and microbial populations and activity (Bagella et al., 2014; Steinauer et al., 2015). Dunbabin et al. (2013) reviewed root architectural modelling and identified the need for more data and conceptual models relating to soil biology, rhizosphere chemistry, soil texture and mycorrhizas, as well as the need to consider root anatomy in models.

The development of SPACSYS (Wu et al., 2007) demonstrates how mechanistic plant (including root) modelling can be applied at the field scale, while Perveen et al. (2014) describe the characterisation in the SYMPHONY model of the impact of microbial diversity and the soil priming effect (the increase in soil organic matter decomposition after fresh organic input) on soil-plant interactions. Linking root modelling to soil models and engaging with plant modellers to drive real-world change (such as improving plant genomes or predicting plant responses to change in the field) has been recognised as a priority by the root modelling community (Dunbabin et al., 2013).

Research priorities: The preceding discussion indicates the need and scope for better communication between grassland modellers, specialised soil and root modellers and experimental researchers, to ensure that grassland models incorporate best practice in these disciplines, with as much detail as needed to effectively fulfil the functions required of them (challenge 13). Contacts through networks such as MACSUR, joint workshops, conference participation, and the development of infrastructure for exchanging information could all support improved communication. Undertaking assessments of the validity of the various functions and approaches used in modelling specific soil processes also represents an important priority in reducing model uncertainty (Sierra et al., 2015). Improved modelling of soil and hydrological processes is considered further in the context of modelling nutrient cycles and GHG balances (challenge 9).

3. Modelling livestock and pasture interactions

The challenge: The impacts of livestock on grasslands, and the reciprocal impacts of grassland management on livestock are multi-faceted and complex. In mixed swards, selective grazing by animals and the spatial distribution of excreta can affect plant species composition and characteristics, through direct influences on inter-specific competition, and indirectly through the uneven distribution of nutrients (Liu et al., 2015; Xi et al., 2014). Grazing intensity is likely to affect soil water retention, poaching, compaction (challenge 2), nutrient leaching and run-off, and GHG emissions (challenge 9). Under conditions where the interaction between animal behaviour and the environment have severe impacts on the sward, the effects on both grassland and livestock become a function of management choices, as grazing pressure is reduced or animals are moved off the pasture. In turn, sward composition, plant cover and condition directly affect feed availability and digestibility (Hopkins and Wilkins, 2006), while external conditions, grazing behaviour and management choices can all affect the disease and parasite risk from the grassland environment (Fox et al., 2013; Smith et al., 2009). Models need to capture such relationships in order to identify the best animal species, breeds and management regimes to maximise the efficiency of grassland-based production under climate change in different environments. Snow et al. (2014) review the various aspects of modelling livestock-pasture interactions, highlighting the challenges relating to the trade-off between model usability and accuracy when attempting to model grazing interactions at animal level, taking into account all the physical variables affecting forage intake. They conclude that complex models are more important when grazing pressure is low (more extensive systems) and in model uses where such detail is needed to model the subsequent digestion of the forage. The importance of the challenges to improving modelling of livestock-pasture interactions is therefore related to the purpose of the modelling effort (challenge 13) and the nature of the system (challenge 11).

Research priorities: Creating an inventory of the impacts of livestock on grassland (and the feedback effects of grassland on livestock) for different livestock species and systems, and mapping this onto the current capabilities of models, were seen by participants as important first steps to improve modelling capacity. The biggest challenges are likely for models focussing on more extensive systems with more diverse swards, because for these systems modelling is more complex, both on the animal and the grassland side of the interaction. The described inventory can facilitate model comparisons, the identification of gaps in knowledge and the testing of different approaches. As in other challenges, improvements to allow both an accurate characterisation of livestock-pasture interactions, and to understand how adaptation strategies might affect such interactions, will require collaboration; in this case between grassland and livestock modellers (including animal behaviour modellers) and between modellers and experimental researchers. Progress will be linked to advances in modelling multi-species swards (challenge 1) and sward nutritive value (challenge 10).

4. Modelling plant responses to environmental change

The challenge: The quantification of plant responses to changing climate is a fundamental challenge for crop grassland models. Climate change can affect grassland plants via changes in a range of environmental conditions (Fig. 1) and plant responses are likely to vary with species and location (Dumont et al., 2015). Plant responses to changes in climate include morphological and physiological adaptation to stress and to raised CO_2 concentrations and changes in photosynthesis, biological nitrogen fixation, and phenology; such responses involve changes in plant genes, proteins and metabolites at different time-scales (Ahuja et al., 2010). White et al. (2012) highlighted variation in methods and focus across experimental sites set up to study plant reactions to climate change, with some impacts (temperature and water) studied more than others (such CO_2 and N addition) so that results relating to individual impacts and interactions between impacts were hard to generalise. Only a few experimental studies have investigated the combined effects of multiple environmental stresses on grassland plants (Ahuja et al., 2010; Bertrand et al., 2008; Dieleman et al., 2012). Limits to knowledge are therefore a constraint on model development in this research area. Current grass and crop models characterise plant growth responses to a range of environmental impacts, including changes in temperature, radiation, nitrogen and atmospheric CO_2 (Höglind et al., 2013; Wu et al., 2007) including impacts on forage nutritive value (Ben Touhami et al., 2013; Jégo et al., 2013; Jing et al., 2013; Thivierge et al., 2016). However, relatively few models incorporate all these aspects; some processes (such as the impacts of CO_2 and variation in N) may dealt with in a basic way, while some interactions are not fully understood (Ramirez-Villegas et al., 2015). In relation to adaptive changes in plant response over time, crop models have been used to explore the impacts of genetic adaptation on yield under climate change conditions, and to define crop ideotypes for climate change resilience (Rötter et al., 2015). However, Ramirez Villegas et al. (2015) highlighted challenges, such as the need to couple genetic and crop models to produce outcomes suitable for incorporation into breeding programmes, and the need to better quantify the robustness of model outputs. In permanent swards with multiple species a range of factors including epigenetic and plastic change and genetic change through natural selection and species sorting, shape grassland responses to the environment. Inter-specific interactions may affect responses to climate change, including changes in biomass production, sward composition and species diversity (Miranda-Apodaca et al., 2015; Olsen et al., 2016). Improved modelling of these types of grassland depends on the advancement of ecological knowledge, and progress in related topics including multi-species, nutritive value and soil and water modelling (challenges 1, 2, 10).

Research priorities: Meta-experiments have been recommended to create international networks of experimental sites which apply the same treatments and recording standards to investigate the responses of swards to environmental change (Fraser et al., 2013; White et al., 2012). Over the long term data from such programmes could facilitate more effective model improvement. Knowledge, data and current model descriptions of the mechanisms underlying grassland plant responses should be reviewed to assess capacity (which species are well characterised, which types of impact and which interactions are incorporated and what are the limitations to the approaches used). This should include consideration of how plant and field level responses are characterised in farm, regional and global models, to evaluate effectiveness and areas for improvement. Ensemble model exercises would be instructive in gaining an overview of current knowledge, including about the climatic and regional boundaries within which grassland models work adequately (Soussana et al., 2010). Drawing together such information would allow model development to be focused on the most important relationships and interactions, in terms of their likely impact on grassland yield, nutritive value and vulnerability to climate change. With respect to temporary grasslands, using approaches used in crop modelling to explore resilient ideotypes for grassland species will be important in better predicting the potential benefits of grass and legume breeding programmes in climate change adaptation.

5. Modelling overwintering

The challenge: Modelling work with the aim of evaluating grassland performance often focuses on the growing season. However, changes in permanent swards during the winter can, especially at high latitudes and in mountainous regions, have important effects on subsequent productivity and nutritional quality in spring and summer (Rapacz et al., 2014). Despite this, plant processes including, hardening, de-hardening and re-hardening, vernalisation, winter respiration and allocation of carbohydrates to reserve tissues (which can all affect the status of the sward during and after the winter) are not sufficiently incorporated in most grassland models. As a result, the sensitivity of grassland yield and nutritive quality to temperature variability, the frequency of extreme cold events and snow cover depth, and management variables affecting winter performance (such as cutting timing and frequency) cannot be satisfactorily assessed with current grassland models. A few previous modelling attempts can serve as a basis for future efforts to improve the representation of winter conditions in grassland models. These attempts include models, which simulate the cold hardiness of winter wheat (Bergjord et al., 2008) and forage grass species (Thorsen and Höglind, 2010) as expressed by the temperature at which 50% of plants in a population die (i.e. the LT50 value). Changes to the LT50 value can be caused by hardening, de-hardening and re-hardening processes during the winter season, which are a function of the prevailing temperature in the upper soil layer surrounding the crown of the plant, and a cultivar-specific maximum hardiness parameter. Snow cover models have also been linked to the STICS model for continuous multi-seasonal simulations of annual spring crops in eastern Canada (Jégo et al., 2014). Recently, a full-year model (BASGRA), for timothy grass was developed by combining a growing season model with cold-hardening and soil physical models for the winter season (Höglind et al., Accepted).

Research priorities: An important next step for model development in this field will be to test the winter-related functions of grassland models against data from experiments simulating projected future winter conditions. Further model development in this field will depend on the availability of experimental data on cold sensitivity and the state of the sward (such as tiller density and leaf, stem and reserve weight during the growing season and over winter). As well as the collection of new data, the systematic organization of existing datasets on these variables according to temperature, precipitation and photoperiod gradients would be beneficial to the development and applicability of winter modules across geographic regions and climatic conditions.

6. Modelling the impact of extreme events

The challenge: The impacts of extreme events on grassland productivity are of increasing concern in relation to food security (Long and Ort, 2010) and the continuing supply of services from grassland systems (Bloor and Bardgett, 2012). While models are improving in terms of their ability to predict the impact of changes in average climate conditions on grassland yields, modelling the impact of extreme events such as droughts, heatwaves, flooding and frost exposure, remains a challenge. A unique definition of an extreme event is also difficult to formulate. Beyond the statistical occurrence of an event exceeding a low or a high percentile threshold, an extreme weather event may be defined as one that has a high impact on society and biophysical systems. Thus, it is a hard-to-predict phenomenon far beyond normal expectations (Peterson et al., 2012). Different types of extreme events often occur together, so that different plant stress factors (e.g. high temperature, low water availability or flooding and waterlogging, evaporative demand and high light intensities) may affect vegetation simultaneously and in different combinations across geographical areas. This generates complexity in climate forcing / plant response relationships across a wide range of temporal and spatial scales. The poor description of this complexity in current grassland models can lead to inaccuracies in simulated processes (Soussana et al., 2010). These limitations become especially apparent when the capacity of grassland plants to acclimate to harsh conditions is substantially exceeded. For example, temperatures that are abnormally low or high often result in lower plant productivity at all subsequent temperatures (Zaka et al., Accepted). In climate change impact studies using grassland models, responses to extreme temperatures and prolonged water deficits are still not sufficiently considered (Reyer et al., 2013; Ruppert et al., 2015). They are also scarce in model calibration and validation datasets due to their low frequency in weather data time series (Ben Touhami and Bellocchi, 2015). The mechanistic relationships between plant processes and the impact of extreme events on these processes have only been fragmentarily documented, and the extent to which plants may be able to respond to extreme weather events remains an open field of research (Reyer et al., 2013). The many interactions between vegetation, soil and the atmosphere, and the role of management practices make our ability to simulate grassland systems limited. Predictions of the impact of extreme events therefore require accurate information about management, animal behaviour and the prior condition of the sward, in addition to data on weather conditions and methods for characterising the interactions between these variables. Few experimental data relate to extreme conditions, with much information collected when long-term monitoring captures the impacts of extreme events by chance (Thibault and Brown, 2008).

Research priorities: To improve modelling of the impacts of extreme events, a review of data and gaps in knowledge in relation to the types of event expected to affect grasslands under climate change is required, including an appraisal of current definitions of extreme events and the thresholds which produce them. An inventory of the capabilities of existing grassland models in relation to extreme events would enable limitations in current approaches to be identified, and options for improvement developed. These could include the development of extreme events functions (affecting transpiration, photosynthesis, tillering, resource allocation, etc.) that could be linked to existing grassland models. Such functions can draw on knowledge from studies about processes of dehydration and recovery of plant communities and functional types (Zwicke et al., 2013) and the explicit representation of hydraulic processes (Tardieu et al., 2015) while also addressing interactions with water and nitrogen cycling (Calanca et al., 2016). Data from ongoing monitoring programmes will have an important role in model validation as new extreme events occur. Grassland data relating to previous extreme events can also be examined to better understand resilience. Current projects, such as MODEXTREME (http://modextreme.org/) and MERINOVA (https://merinova.vito.be/Pages/home.aspx) offer collaborative arenas for making progress in overcoming this challenge. The synthesis and sharing of outcomes from these projects in the wider modelling community will be important in the future development of modelling capacity.

7. Incorporating plant pests and pathogens into models

The challenge: Pathogens and pests can affect crop and grassland yield in a range of ways (Gregory et al., 2009). Climate change is expected to have complex impacts on crops and their interactions with pathogens and pests, including increased plant vulnerability resulting from their genetic responses to the effects of environmental change, changes in pest and pathogen fecundity and growth rate, and changes in assemblages of pest antagonist species (Gregory et al., 2009; Rapacz et al., 2014; Zulka and Götzl, 2015). These relationships are complex. Although interactions between plants and pathogens in mixed species swards are not fully understood, there is evidence that pathogens can play an important role in maintaining sward diversity and even in maintaining higher productivity in diverse swards, with swards made up of few species more vulnerable to pests and pathogens (Bever et al., 2015).

In general, grassland models do not incorporate the impacts of pests and pathogens currently affecting European grasslands, nor the changes in pathogen spread expected as a consequence of climate change. At present the characterisation of pathogens and pests in the modelling of leys is fairly limited, for example assuming constraints based on the 'disease class' of different crops in crop rotation models (Annetts and Audsley, 2002). Looking beyond insect and microbial pests and pathogens, grazing by other species, such as waterfowl, can also cause significant problems for grassland productivity (Merkens et al., 2012), and to the authors' knowledge, this has yet to be addressed in grassland modelling.

Research priorities: Gregory et al. (2009) highlight the need for modelling the impacts of pests and pathogens under climate change that takes into account complex interactions of these species with other biotic and abiotic variables. This should go beyond current coupling of climate change and weather-based disease forecasting, or the prediction of future pest and pathogen distributions based on information about their ecological niches and climate mapping.

Further developing process-based modelling approaches is important to better understand the impact of pathogens and pests under climate change conditions. In an example of this kind of approach, Whish et al. (2015) combined two process-based models – a pathogen population model (DYSIM) and the APSIM crop model – to investigate the impact of a wheat rust on yield. Such mechanistic approaches may be used to provide the insights required to model more complex multi-species interactions with pathogens. Assessing the impacts of adaptation measures, for example in the form of resilient cultivars, changes in crop rotations or the conservation and development of plant diversity in grasslands will also require improved knowledge of pest-pathogen interactions. A further priority will be to model how plot-level interactions are mediated by landscape characteristics; for example, the impacts of biodiverse semi-natural habitats which are known to promote antagonist species of pests (Zulka and Götzl, 2015), linking to the idea of resilient Climate Smart Landscapes (Scherr et al., 2012).

The collation of existing knowledge about key pests and pathogens of grasslands across different regions, including information about their ecology (such as their likely response to climate change and control by antagonist species) along with an assessment of models developed across disciplines to investigate them, would be a first step to improving modelling capacity. Such an inventory could be used as a basis to review the options for modelling the future effects of these pathogens under climate change, in mono-cultures and in multi-species swards.

3.2. Climate change effects on grassland systems outputs

8. Modelling the provision of ecosystem services

The challenge: At present, many agricultural grassland models focus on productivity, without taking into account the value of ecosystem services provided by grasslands (Kipling et al., Accepted). A number of authors have identified a range of beneficial roles played by grassland systems (Hönigová et al., 2012; Zhao et al., 2003) including: soil erosion control and rainfall regulation (critical in the context of increased occurrence of extreme events under climate change; challenge 6), soil carbon accumulation and nutrient cycling (challenge 9), air quality purification, biodiversity maintenance and the sustaining of cultural diversity. In relation to each of these services, models need to be able to characterise the impacts of climate change and associated changes in management strategies.

A range of modelling approaches is currently used to evaluate the impact of farm- and policy-level decisions on biodiversity, and to incorporate biodiversity into multi-objective models at the regional scale (Kipling et al., Accepted). There is also potential for, and some examples of, agricultural models being used in conjunction with ecological models to explore interactions between production, management choices and biodiversity (Tixier et al., 2013) while modelling tools are being developed to evaluate grassland ecosystem services more generally (Campion et al., 2014). The need for more research on carbon sequestration (challenge 9), water regulation and conservation of soils (challenge 2) across EU climate regions has also been recognised (Soussana et al., 2004). Advances in modelling these relationships rely on developments in experimental research to understand more fully the mechanisms underlying the provision of ecosystem services and their relationship to production (Pilgrim et al., 2010).

Given that ecological and social resilience to extreme events are intertwined (Adger, 2000) and that diversity and modularity are important components of social resilience (Carpenter et al., 2012) the role of grasslands in maintaining cultural diversity is no less important than the ‘physical’ services discussed in the context of climate change. In this respect, developing the capacity to model traditional extensive systems that have received less attention in the past (challenge 11) and participatory engagement with stakeholders to develop relevant models and explore adaptation alternatives, are important priorities (challenge 13).

Research priorities: Participants suggested that a first step towards the better characterisation in grassland models of ecosystem services and the impacts of climate change upon them would be to identify modelling capacity with respect to each pairing of ecosystem service and climate change impact across different European regions. This process could draw on published work and reports on ecosystem services, such as Hönigová et al. (2012), and climate change impacts, such as Iglesias et al. (2012), and on model inventories currently available in the literature. This exercise should be inclusive of ecology, vegetation, hydrology and soil models, to reveal not only gaps in capacity, but also areas in which models from these different disciplines could be used together to provide assessments of grassland systems encompassing the evaluation of non-commodified services.

9. Modelling nutrient cycles and GHG balances

The challenge: Modelling of GHG emissions from ruminant production systems has received much attention, but challenges still remain in the characterisation of anaerobic slurry digestion and CH_4 leakage, NH_3 and N_2O emissions from manure, and the interaction of nitrogen with soil and weather in relation to NO_3 leaching (Kipling et al., Accepted). Focusing on grasslands, understanding and modelling soil processes is central to estimating nutrient flows (challenge 2).

Reviewing models of carbon release arising from soil organic matter (SOM) decomposition, Sierra et al. (2015) identified the need for more data on and better characterisation of SOM decomposition processes at high temperature and extremes of moisture, and for a critical assessment of the range of functions used to represent such processes in different models. Recent modelling by Perveen et al. (2014) (see also challenge 2) incorporated the characterisation of the soil priming effect and microbial diversity into the SYMPHONY model, and used it to examine impacts on soil and plant interactions and carbon and nitrogen dynamics under climate change.

Studying combined impacts of environmental change on nutrient cycling, rather than the impact of individual changes in isolation, is an important challenge to be met (Sierra et al., 2015). Recent research has found that plant diversity may play a more important role than temperature in determining the communities of microbes involved in carbon, nitrogen and phosphorous cycles (Steinauer et al., 2015), and that the expected increase in soil carbon emissions arising from higher temperatures may be mediated by consumption of fungi by soil invertebrates (Crowther et al., 2015). These findings highlight the importance of considering biotic and abiotic processes together. Increasing the capacity to model such interactions will therefore require collaboration between modelling communities and with experimental researchers.

Research Priorities: Participants suggested that tests on the impacts of manure management on emissions (for example, the method and timing of applications and manure type) were required to support improved grassland modelling in this area, with more data on nitrogen fluxes and pools also important. The development of models characterising closed nitrogen cycles and incorporating the history of nitrogen in plants and the soil, was considered another priority for improving modelling capacity. Overall, improving model equations relating to N_2O and CH_4 emissions, as well as improving the definition of carbon pools, and work to relate N_2O emissions to the efficiency of nitrogen uptake by plants in models, are important areas for development, with the aim of tackling some of the complexity described in this section. These steps can help to reduce model uncertainty and increase the capacity to model nutrient cycles and emissions under different climate change scenarios.

10. Modelling nutritional variables required to predict animal performance

The challenge: Modelling sward nutritional value (see also challenge 1) is of particular importance for understanding the interactions between grasslands and livestock nutrition. Changes in nutritional value will alter the need for other feeds and supplements and affect productivity and the quality of final products. Impacts may also arise through altered intake by livestock caused by changes in grazing behaviour (challenge 3). The nutritional value of ruminant feed includes a range of variables: nitrogen fraction (total nitrogen, nitrogen solubility, nitrogen degradability, acid detergent insoluble nitrogen); potentially fermentable fraction (water soluble carbohydrates, pectins, starch and cell walls); non-fermentable fraction (volatile fatty acids, lactate, lipids) (AFRC, 1998). Climate change is expected to affect the nutritive value of grassland swards through nutritional changes in individual species, and changes in species composition, with impacts varying according to conditions (for example mountain versus Mediterranean grasslands) and species type (Dumont et al., 2015). Where grasslands are cut for silage, hay or in 'cut-and-carry' systems, rather than grazed directly by livestock, nutritive value will also be affected by cutting time, and by subsequent treatment and storage; climate change is expected to alter the optimal timing and number of silage cuts (in terms of yield and nutritive value) per year in northern Europe (Höglind et al., 2013). Given this complexity, the detail with which models characterise nutritive value must be tailored to reflect the aims of individual modelling exercises (challenge 13). The modelling of changes in grassland yields (Graux et al., 2013; Vital et al., 2013) is well developed. However, the characterisation of nutritive value in grassland models has been in general limited to species-specific responses to conditions, for example in timothy (Duru et al., 2010; Jégo et al., 2013) rather than changes in value in multi-species swards (Kipling et al., Accepted).

Research priorities: Grassland and livestock modellers and animal nutritionists need to work together to identify the most important nutritional parameters for incorporation into grassland models in relation to different applications. This should include gaining an overview of the extent to which current models are capable of characterising these parameters. Harmonising how nutritive value is reported and calculated for modelling, and in model outputs, will also require cooperation, with the aim of allowing models to be applied, compared and evaluated across Europe. These collaborative developments can facilitate the creation of more models able to provide the nutritional data required to support accurate predictions of animal performance under climate change.

3.3. Mediation of climate change impacts by site, system and management

11. Modelling different regions and production systems

The challenge: Models are often developed to answer questions relating to specific systems within a particular region. Llewellyn et al. (2007) found that stakeholders are most interested in local information, and that presenting such information can aid understanding and uptake of modelled solutions. As a result, models may not perform well when applied to other conditions. For example, the focus of previous modelling has often been on intensive and non-organic systems, such as that reported by Jing *et al*. (2012) and Jégo et al. (2013). In part, this may reflect the complexities of modelling heterogeneous extensive swards likely to contain multiple species (challenge 1). There are also gaps in the modelling of region-specific systems. For example, grassland models designed for temperate systems mainly characterise perennial species, while Mediterranean grasslands are dominated by annuals. In addition, perennial species in these systems undergo a period of summer dormancy due to harsh conditions in the summer months. Although some models, such as STICS (Ruget et al., 2009) consider summer dormancy in perennial species, relatively few models have focussed on these types of grassland, despite the expected negative impact of climate change on Mediterranean regions of Europe (Iglesias et al., 2012). In this case, the systems in question differ between regions, but differences may also cut across regions.

Research priorities: In order to realise the ideal of having models able to predict climate change impacts and the effectiveness of adaptation and mitigation strategies across systems and regions, undertaking a systematic assessment of current capacity was considered important. This could be achieved by using and further developing model inventories such as those created as part of the MACSUR project (Bellocchi et al., 2013), in order to match models to the systems and regions they were designed for, or could potentially be suitable for. Assessments of the potential for widening model applicability can draw on the findings of investigations that have used generic approaches to model biophysical processes across a variety of regions (Yuan et al., 2014). Recent work comparing models from different regions, such as carried out within the FP7 project MultiSward (http://www.multisward.eu/multisward_eng/) the MACSUR project (Sándor et al., 2015; 2016) and the Agricultural Model Inter-comparison and Improvement Programme (AgMIP) (http://www.agmip.org) can provide further evidence about the applicability of models to different environments and systems. This baseline information could inform new modelling research and data collection in order to fill identified gaps in capacity, and to ensure that climate change impacts are effectively modelled across regions and systems. The applicability of models to other systems and regions will depend on the characteristics of the focus system/region and of the model itself, but also on the level of detail required to achieve specific aims (challenge 13).

12. Modelling adaptation strategies

The challenge: Modelling adaptation strategies requires both that the designs of models allow changes in biophysical and/or economic variables to drive, and be driven by, management choices over successive model cycles, and that reactions to changing circumstances realistically characterise the behaviour of decision makers. The first part of this challenge therefore relates to the development of capacity to model the physical impacts of grassland management such as, cutting and grazing and interactions with re-growth and flowering, fertilization and interactions with pest and disease susceptibility, changes in soil organic matter, and changes in the system being used, for example, from mono-culture to mixed pasture or from permanent to temporary grassland. Adaptation also includes plant breeding strategies (see challenge 4); models can be used to investigate the traits or trait combinations of benefit for species under climate change in different contexts. However, so far models have rarely been applied to grassland species (Van Oijen and Höglind, 2015), and progress will require more data on the genetics of different plant traits, as well as new model methodologies.

Models will need to characterise how different management strategies interact with other variables and with outputs in terms of yield and quality; for example, the effect of a wet harvest season on herbage and silage nutritional value and on associated costs, such as the need to buy supplementary feeds. In this context, linking to other types of modelling will be important, for example to characterise the livestock health and environmental risks associated with manure application given expected climate-related changes in pathogen spread (Venglovsky et al., 2009). Recent models such as PaturaMata have been specifically developed in order to design management strategies for farms under climate change (Dusseux et al., 2015) and many current grassland models can be asked to respond to specific changes. Some process based farm scale models, such as the Integrated Farm Systems Model (Rotz et al., 2014) and some grassland models (Vuichard et al., 2007) are able to explore the impact of different management strategies (such as changes in cutting regimes) under climate change (Thivierge et al., 2016) but further development is required to improve the scope of adaptation options covered, and the characterisation of interactions between different strategies (Del Prado et al., 2013). Such development should take into account the need to explore the potential of more 'explorative' adaptation strategies (Martin et al., 2013) such as the introduction of silvo-pasture (Broom et al., 2013).

Adaptation includes not just changes of management, but also changes of system. At regional level, economic land use models have been applied to forecast changes in agricultural land use as a result of climatic and socio-economic changes, based on profit thresholds for different land uses (Audsley et al., 2015). As farmers' choices about the adoption of adaptation strategies are known to be affected by both economic and non-economic considerations (for example, their perception of climate change risks) (Llewellyn, 2007; Lyle, 2015) the second part of this challenge (to more accurately characterise the uptake of adaptation strategies) is also complex.

Research priorities: To develop the capacity of models to characterise the impacts of adaptation strategies will initially require the collation of resources detailing available strategies for different systems and regions, such as provided by Iglesias et al. (2012) and Iglesias and Garrote (2015), including current knowledge related to their efficacy and the mechanisms via which they work. Assessments can then be made of the availability and limitations of modelling in relation to different strategies and their potential interactions with other management and policy decisions. Options for incorporating current understanding of stakeholder decision-making into bio-physical models need to be explored, in order to ensure that models better characterise the likely uptake of adaptation strategies. One approach would be to use the identified adaptation strategies to develop context-dependent adaptation scenarios, fitted to the expectations and knowledge of relevant stakeholders. Finally, management modules (as well as the characterisation of biophysical relationships) will need to be validated for climate change conditions.

3.4. Cross-cutting methodological challenges

13. Making models 'fit-for-purpose'

The challenge: The different contexts in which grassland models are used require those models to have very different characteristics, in terms of complexity (including the types and resolution of data they require; challenge 15), the scales of inputs required (challenge 14) and outputs delivered, and the level of capacity to model management changes and stakeholder choices (see also challenge 12). Mechanistic models have great value for understanding more about complex processes and interactions, while at larger scales and for more practical applications simpler mechanistic and empirical models, informed by this deeper understanding, can be effective predictive tools.

Therefore, the apparent trade-off between model usability and accuracy can be seen instead as an iterative development process (Kipling et al., Accepted). In this context, the type of model applied to a particular problem should reflect the nature of the problem and the needs of the stakeholders concerned (Ramirez-Villegas et al., 2015). This can be achieved through the iterative involvement of relevant stakeholders in model development and evaluation (Bellocchi et al., 2015). To achieve the best outcomes, stakeholders should also be able to easily choose between available modelling tools, requiring them to be shared and packaged to allow comparison of their usefulness in different contexts (Voinov and Bousquet, 2010). Modelling platforms which support the development of interchangeable sub-models, can produce modular modelling tools that are easily adapted for specific and emerging uses (Holzworth et al., 2015). In crop and grassland modelling, the Biophysical Models Applications (BioMA) framework (http://bioma.jrc.ec.europa.eu) is a good example of a software platform that supports modular model development and evaluation.

Research priorities: A key first step to developing more adaptable models is to gain an overview of their current capabilities in relation to different potential uses. Creating a checklist style inventory which clearly compares model applicability in relation to specific tasks would both highlight scales and types of modelling that are missing, and help stakeholders and policy-makers to select the most appropriate modelling tools to support their activities. Model inventories within projects such as MACSUR (Bellocchi et al., 2013) form the basis for the development of such a resource, while online hubs such as Agrimod provide the potential to share this information with wider scientific and stakeholder communities. A checklist inventory could be a starting point for reviewing the options for developing further flexibility and accessibility. While modular modelling and open access modelling can be valuable, the challenges to collaborative working need to be recognised in a competitive scientific environment. In this context, a resource presenting existing and developing tools in a format accessible to stakeholders may create more favourable conditions for mutual learning between modellers, while maintaining the valuable diversity required to tackle climate change related issues which can vary by region and system (challenge 11).

14. Linking different scales of modelling and data

The challenge: Grassland simulations can be defined at different spatial scales ranging from plot to region. Input data are often supplied, and output data may be produced, at different scales than that at which the analysis is performed, thus requiring the application of down- or up-scaling techniques (Höglind et al., 2013). The level of detail of input and output data varies with the model (and often with the country) and thus the required level of upscaling / downscaling. The spatial extent and resolution of data is therefore a critical issue which must be accorded special attention (Zhao et al., 2015) considering that changing spatial resolution by aggregation or disaggregation of data (e.g. using field-scale impact models with input data at scales other than that for which they were developed) bears the risk of missing the relevant scale of a process or phenomenon. Specifically, climate models produce large scale output data while micro-climatic changes can be important for grassland modelling. Extrapolations of local soil properties to larger regions can also help assess the requirement for soil input in regional estimations (Persson et al., 2015). Insufficient automation of composition and execution, and scalability of approaches can be one of the reasons for the absence of comprehensive, computer-aided, and spatiotemporal assessments. This is true especially in local contexts where automated procedures become essential to link downscaled climate scenarios to biophysical outputs and socio-economic impacts (Walz et al., 2014).

Research priorities: The systematic evaluation of the software and techniques available for down-scaling of data is required in order to understand the limitations and strengths of the different approaches, and to gain insight into the scale dependence of grassland models (Zhao and Liu, 2014). Better access for modellers to down-scaling techniques is also important, alongside evidence on their performance. In addition, systematic tests of model sensitivity to changes in data resolution, including in relation to climate data, are important in order to establish where scaling techniques, or the provision of data at a different resolution, would be most beneficial. Eza et al. (2015) describe the application of a modelling platform for climate change vulnerability studies (and their incorporation into management and planning), where grassland simulation capabilities are at the core of integrated and automated procedures (including down- and up-scaling approaches) usually employed in isolation.

15. Providing data for models

The challenge: Models rely on experimental data for their development, evaluation and application to different problems. Data issues vary for different areas of grassland modelling. They can be categorised as 1) The need for data from new experimental work 2) Quality and completeness of available data, 3) Data accessibility, and 4) Variation in data measurement and recording:

1) Datasets which include information about previous management (for example, the age of the grassland, previous fertilisation, cutting or grazing) are often lacking, for example in relation to data on soil carbon and carbon sequestration. In general there have been

fewer studies investigating interactions between variables, for example in studies of soil processes (challenge 2) with a focus on single variables more usual. Modelling can increase understanding of complex systems and the interactions within them (Van Paassen et al., 2007). In this way models can highlight priorities for future experimental research. Developing the relationship between modellers and experimental researchers can therefore drive well-focussed experimental research and data collection (Kipling et al., 2014).

2) The detailed information required for some aspects of grassland modelling can be obtained from experimental sites set up for long term data collection, such as micrometeorological flux measurement sites (Baldocchi et al., 2001). However, data from other sources need better evaluation in terms of the methods used, their compatibility with specific models, and the level of detail they include. Through the MACSUR knowledge hub, Kersebaum et al. (2015) developed a quantitative classification framework to evaluate the quality and consistency of existing agricultural datasets for use in crop models. This framework is likely to be applicable for the identification of data for grassland models, especially for models used to characterise both grassland and cropping systems (Bellocchi et al., 2013). New approaches to data collection include the use of remote sensing (Courault et al., 2010; Verrelst et al., 2015) and the development of virtual weather stations that combine a range of data sources to improve rainfall estimates (Racca et al., 2011). These advances can improve data accuracy and provide new data-sources of potential value for grassland modelling.

3) Open access data platforms such as FLUXNET (Baldocchi et al., 2001) provide examples of how standardised collecting, processing and delivery of data can be developed, and that data shared. In other areas, online resources to share meta-data have been created, for example for soil data at European and global levels (Kipling et al., 2015) and sites specifically focused on sharing information about models and data such as Agrimod provide important resources for grassland modellers.

4) Differences between nations and research groups in the way that variables are measured and recorded can cause problems, for example, differences in the definitions of forage nutrient values (challenge 10) can hinder the use of data for modelling. Differences in terminology and approach have been recognised as barriers to inter-disciplinary collaboration (Siedlok and Hibbert, 2014), and overcoming them requires enhanced communication and understanding between researchers across Europe. The

implementation of standardised collection, processing and delivery of data is particularly important when undertaking model inter-comparison studies.

Research priorities: Improved communication between modelling groups and experimental researchers is vital to ensure that shared meta-data on available datasets allows their identification and evaluation for use by grassland modellers. This will require modellers to effectively communicate the data types and standards that they require, developing and sharing protocols for data evaluation such as those described in this section. The need for such developments is common to a range of agricultural modelling disciplines, and inter-disciplinary collaboration is therefore vital in this area to prevent duplication of effort. Networks such as MACSUR, AgMIP and the Global Research Alliance (http://globalresearchalliance.org) are essential in providing arenas in which modellers can collaborate to create and enhance these community resources. The development of networks of experimental sites and coordinated experiments across nations to investigate climate change impacts on grasslands (White et al., 2012) would also support model development, by providing high quality, comparable data.

4. Synthesis

The fifteen challenges for grassland modelling identified here (Table 1) cover all aspects of modelling. Although many of the challenges have been discussed in previous reviews, such as Bryant and Snow (2008), Snow et al. (2014) and Holzworth et al. (2015), to the authors' knowledge this has been the first attempt to comprehensively assess the challenges and priorities for European grassland modelling in the context of climate change, using a collaborative horizon scanning approach. In identifying the research priorities associated with each modelling challenge, participants repeatedly highlighted the need for a clear and comprehensive collation and sharing of information on current grassland modelling tools and methodological approaches. Across the challenges considered, the benefit of such resources to drive both the development of modelling on specific topics, and the development of more adaptable, accessible modelling platforms and approaches was highlighted. These priorities suggest that, despite the development of a range of research networks and collaborative groupings relating to agricultural modelling, a high degree of compartmentalisation still exists between researchers in different research groups, institutes and nations. As well as spurring and focussing the development of new experimental and modelling research, rich, shared inventories of models and data are also important for stakeholders and policy-makers seeking the most relevant modelling tools to meet their needs (challenge 13). Access to effective modelling tools is a vital element of supporting stakeholders in making effective decisions (Voinov and Bousquet, 2010). The current state of grassland modelling can be illustrated by ad hoc interactions between modellers, experimental researchers and stakeholders (Fig 2, left panel). Addressing the modelling priorities identified in this exercise would move the community towards greater coherence, with shared model and data inventories driving research and collaboration, and supporting stakeholder choices (Fig 2, right panel).

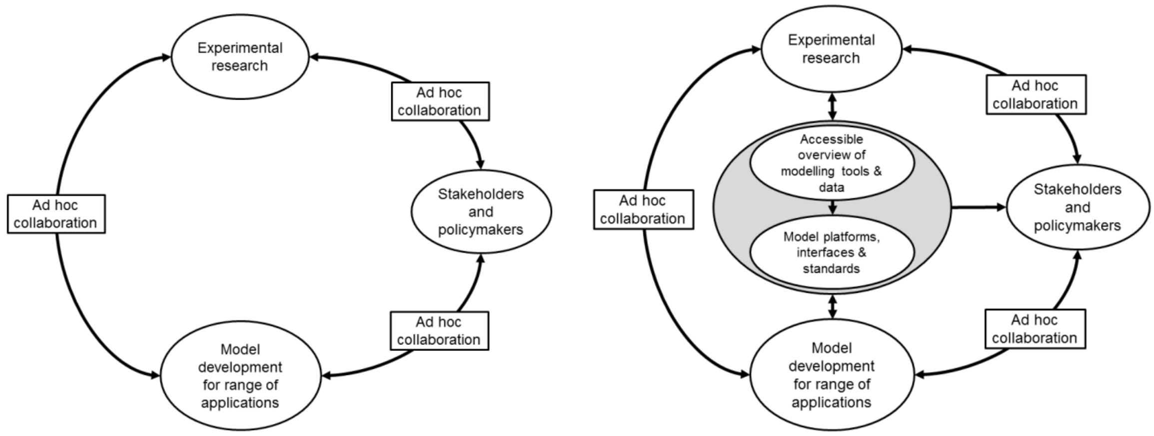

Figure 2: Modelling, experimental research, and stakeholder interactions without community resources (left) and with community resources (right).

Across the agricultural research community, the need for joined up approaches to tackling the issues of climate change have long been appreciated (Soussana et al., 2012) and current network initiatives are starting to move agricultural modellers towards the realisation of a more joined-up, focussed modelling community, as some of the resources developed in MACSUR, GRA and AgMIP (Antle et al., 2015; Bellocchi et al., 2013; Kersebaum et al., 2015; Yeluripati et al., 2015) demonstrate. However, long term support and governance will be required if these efforts are to be successfully extended (Kipling et al., Accepted) given the barriers to scientific collaboration, especially across disciplines (Siedlok and Hibbert, 2014). While initiatives such as MACSUR have been shown to have a positive impact on levels of collaborative engagement, there also appears to be more work to do to engage with researchers beyond a well-connected core (Saetnan and Kipling, Accepted) and to provide the more comprehensive and accessible resources for grassland modellers and stakeholders described here.

In relation to the more specific challenges for European grassland modelling, the need to learn from advances in other fields was a noticeable component of many research priorities, for example: the incorporation of understanding and approaches from soil and root modelling (challenge 2 and 9), from livestock modelling (challenges 3 and 10), from plant and ecosystem modelling (challenge 1, 4, 5, 8) and from those involved in research and modelling of stakeholder decision-making (challenge 12). Across the challenges relating to individual climate change impacts, the reliance of grassland models on the availability of suitable data (challenge 15) for further development was also clear. Finally, meeting the methodological challenges (13 – 15) will require technical dialogue between modelling disciplines which might successfully adopt the same methods despite widely differing subject matter. Better sharing and comparisons of models presented in accessible inventories, the subsequently improved visibility of opportunities for collaboration (Fig 2) and networking between disciplines, will be required to make these types of link in an effective way.

A horizon scanning approach has allowed the collation of views of grassland modellers and researchers from across Europe, while subsequent consideration of the literature validated opinions expressed in the workshop session and via questionnaire. It is hoped that the presentation of these findings will help grassland modellers to identify new directions and collaborative opportunities in their research, and guide policy makers involved in shaping the research agenda for European grassland modelling under climate change.

5. Conclusions

The horizon scanning exercise presented in this paper identified 15 challenges to European grassland modelling in the context of climate change (Table 1), considered the current state of modelling in relation to each challenge, and presented pathways to improving model capacity. The responses of participants to this exercise highlighted the need for the creation of shared resources within the grassland modelling community, in order to 1) allow stakeholders to identify and select modelling tools to suit their needs, and 2) drive experimental and modelling research by focussing attention on gaps in knowledge and opportunities for collaboration (including engagement with stakeholders during model development). The creation of such resources will require long-term support and governance in order to overcome the barriers to such cooperative endeavours in a competitive scientific environment. However, the complex, multi-faceted nature of climate change makes such developments essential.

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