Consultative Group on International Agricultural Research /

Earth Systems Science Partnership sponsored

Climate Change, Agriculture and Food Security Challenge Program:

Report on the Meta-Analysis of Crop Modelling for Climate Change and Food Security Survey

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KEY FINDINGS

- An improvement in the quality of data used for calibration and testing purposes and as input to the models was seen as one of the most important ways of improving models.
- This is associated with a high requirement for improved availability of, and ease of access to shared data sets for calibration and model input.
- Use of models to improve understanding of processes was seen to be the best outcome, but policy development and climate change mitigation were not seen as key outcomes of model use.
- There is a paradox in that the main strengths of models were seen to be the detail of process representation, but not the skill in representing observed phenomena.
- The main strengths of the models were the representation of detailed processes, whereas the robustness in the quality of outputs was rated much lower.
- For improved modelling of climate change impacts, the best developments in process representation were seen to arise from better understanding and model representation of crop responses to extremes (particularly temperature and water limitations) and to elevated CO_2.
- The main food crops are represented by models, but the focus of application is cereals, maize and rice.
- Models were seen as being easily transferable to new locations, but limited by the availability of location specific data (e.g. soils, management, and weather).
- About half of respondents said their models had not been calibrated against elevated CO_2 experiments.
- Model evaluation and testing would be improved by availability of better quality data.
- Models need to be tested more against extremes of rainfall and temperature.
- Some models incorporate damage by insect pests, pathogens and physical damage (lodging, frosts, flooding), but there is a need for closer dynamic linking between weather, soil conditions and crop status with the characteristics of the individual form of damage in order to better represent observations.
- Modelling has been applied in most parts of the world, but the results indicate that the Middle East, Central Asia, African and Russian Federation countries have been under represented by modelling efforts.
- The quality and level of detail of documentation varies considerably between models, with clear potential for improvement.
- Funding was seen as the main factor limiting further model development.

INTRODUCTION

This survey of crop modelling was commissioned by the Consultative Group on International Agricultural Research (CGIAR) and Earth Systems Science Partnership (ESSP) sponsored Climate Change, Agriculture and Food Security - Challenge Programme (CCAFS).

The aim of the survey was to collate information, opinions and expert feedback across a wide range of people involved, either directly or in-directly, on crop model development and application. The purpose of this was to provide information representing the crop modelling community's current views on the state of model development, and how they can be improved to support research and decision making on issues of climate change impacts, mitigation and adaptation, and food security. From this it is hoped that improvements in crop modelling capabilities can be utilized to achieve food security, enhancing livelihoods and improving environmental management in the developing world, considering the threats posed by climate change.

About the survey

Response rate

Invitations to participate in the survey were sent via individual email addresses and listserv mechanisms, with a request in the invitation to forward to colleagues and other contacts. This makes it infeasible to determine the actual response rate, as it is likely that estimates of the total number of invitations received could vary by several thousand. Based on the initial dispatch of invitations, an estimate of about 5,000 invitations received appears reasonable. The survey was accessed 495 times, but only 457 provided responses, giving an approximate 1 in 10 (c. 10%) response rate.

Survey structure

The survey was made up of questions that elicited information that can be separated into the following categories:

1. Meta-data:
    a. About the model, its developer, structure, code, scale of application etc.
    b. Contact details, further sources of information, websites, documentation.
    c. Application coverage, transferability.
    d. How the model is run, skills required, data requirements.
2. How and where the model has been applied.
3. Processes modelled:
    a. Water, nitrogen, plant growth.
    b. CO_2 responses, greenhouse gas emissions.
    c. Processes or factors not represented.
4. How representation of processes can be improved.
    a. What are the constraints to development
5. Where the gaps are in modelling capabilities:
    a. What crops are not represented.
6. What are the constraints to further development.
    a. Calibration data.
    b. Model structures.
7. Feedback and opinions.

Individual responses, comments etc., can be tracked to the original survey to investigate specific responses, particularly for text responses detailing comments and suggestions and sources of further information.

SURVEY ANALYSIS RESULTS

ABOUT THE RESPONDENTS

There were a total of 457 responses, varying in the level of questions answered (141 where totally completed). Of these 42 considered themselves as model developers, 191 as model users, and 155 as both model developers and users, whilst 69 were 'others' (agronomists, lecturers, plant breeders etc).

Responses were from a total of 74 countries, with the number of responses per continent being: Africa 112; Asia 92; North America 67; South America 38; Europe 121; Australasia 26. This coverage is likely to be a function of the effectiveness of the dissemination of the invitations to contribute to the survey, rather than a true reflection of the distribution of people involved in crop modelling.

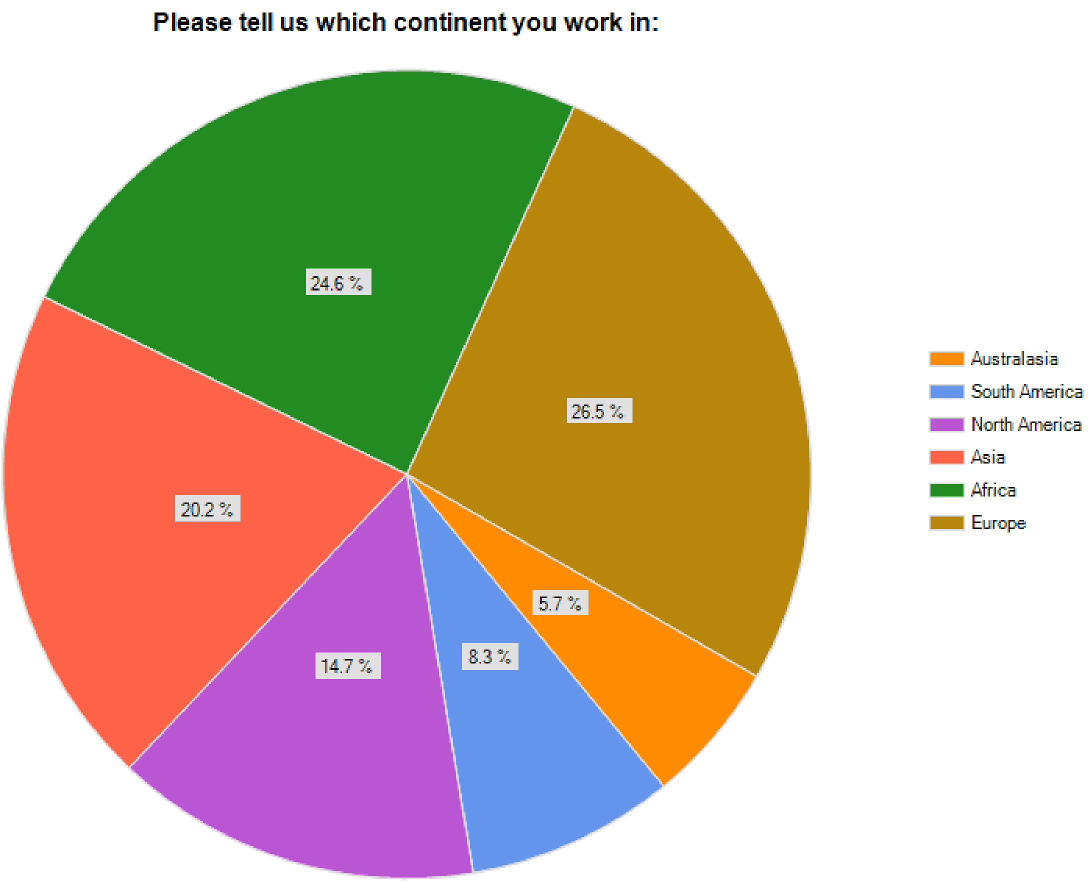

FIGURE 1 CONTINENTS IN WHICH RESPONDENTS WORK IN

REPORTED MODELS

A total of 122 separate models were reported, though with some respondents providing answers based on use of multiple models. Not all responses were for crop models *per se*, with 37 counts for 'not crop specific but part of an environmental or agricultural process'. See Appendix 1 for a list of models reported and number of responses per model. It should be noted however, that the number of responses per model does not reflect the distribution of the numbers of people using a particular model, as it is known that several modelling groups organised collective responses, and that some invitation dissemination was more effective for some modelling groups than others.

As such, the large number of responses reporting on the DSSAT (72) and APSIM (17) models (out of a total of 233 responses) will strongly influence the overall pattern of responses, but these two together represent only 38% off all responses.

MODEL STRUCTURE, SCALE AND MODE OF OPERATION

STRUCTURE

From 159 responses, 91 (57%) said the model is process based / mechanistic, 24 (15%) were modular, 22 (14%) were empirical, 16 (10%) were object oriented, with 10 'other' types. Comments clarified that some models were process based but not mechanistic, mechanistic and modular, mixtures of empirical and mechanistic.

SCALE

The fundamental scale of representation within the models was (out of 141 responses): plant part 27 (19%), plant 23 (16%), field 58 (41%), region 17 (12%), with 16 'others'. Comments indicated that other scales included cell, farm, multiple scales and grids.

MODE OF OPERATION

From 146 responses, 104 (71%) stated the models were operated via a user interface, 25 (17%) via a command line, 12 (8%) were spreadsheet based. Comments indicted that models could be operated by combinations of modes (i.e. shell and command line, interface and command line), linkages with other software (Excel, R, Matlab etc) and through web based systems.

Model usages, outcomes, and transferability

What are the models used for?

The primary and secondary purposes of the models are clearly seen to be decision support, climate change impacts and/ or adaptation, productivity / yield prediction or forecasting and research for crop management improvement (Table 1). These results should be contrasted with those seen in Figure 2 that details the views on what the best outcomes of model use were.

TABLE 1 PRIMARY AND SECONDARY PURPOSES OF THE MODELS (COUNT, %)

	Primary purpose	Secondary purpose
Decision support	53 (25)	28 (13)
Climate change impacts and / or adaptation	51 (24)	61 (28)
Productivity / yield prediction or forecasting	46 (22)	51 (23)
Research for crop management improvement	41 (19)	42 (19)
Research for crop genetic improvement	14 (7)	10 (5)
Education / training	7 (3)	15 (7)
Operations optimization	2 (1)	11 (5)

What are the best outcomes from using the models?

The results indicate (Figure 2) that it is the use of models leading to a better understanding of processes that is the best single outcome, but collectively (1^{st} to 5^{th} ranking) this is matched with guiding current management adaptations, and to a lesser extent, providing better forecasting of yields / productivity. It is worth noting the apparent limited connection between the use of models and influence on policy development and use in guiding climate change mitigation.

Additional outcomes detailed included land use evaluation and planning using input of climate variability and climate change, training/education, policy development and preventing pre-harvest mycotoxin contamination.

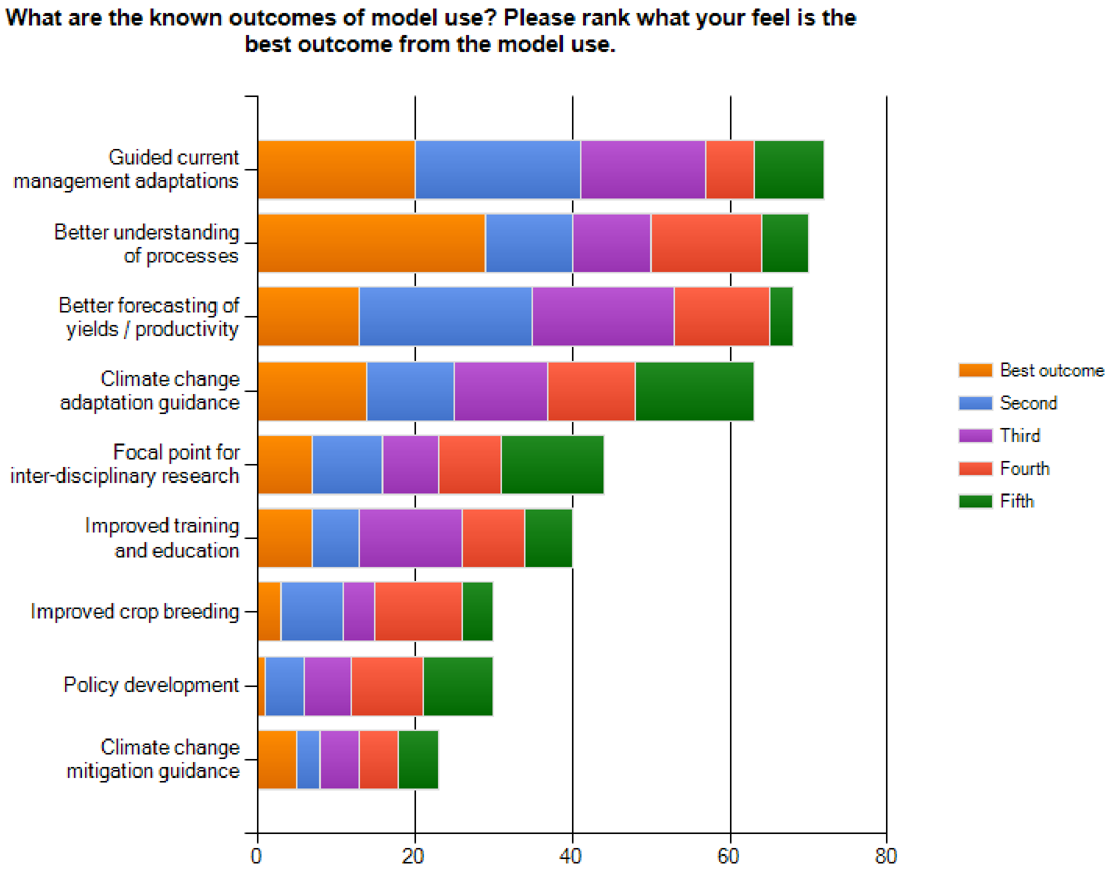

FIGURE 2 MODEL USE AND BEST RATED OUTCOMES (X AXIS IS THE COUNT OF INDIVIDUAL RESPONSES)

Suggested ways of improving the outcomes included:

- Co-operation between modelling groups, synthesising shared data, better teamwork.
- Improved quality / extent of data sets, with easier access (to improve efficiency of researchers' time).
- Greater interaction between modellers and stakeholders (farmers, policy makers etc), better targeting of relevant issues and feasible solutions through participatory research, further observation of the outcomes by experts. Use of models in policy formulation.
- Improving accuracy of model via better connection between processes.
- Better education / training; of processes, application of the models, inclusion of model use within academic curriculum, more modelling workshops.
- Comparisons between models.
- Cross-location calibration and evaluation.
- Integrated assessments of whole farm implications.
- Greater levels of interdisciplinary (i.e. chemistry, physics, economics, participatory approaches). Creation of multidisciplinary teams with problem-solving focus.

- Linking to GIS platforms for data input and output, and improving calibration using remote sensing imagery.
- Better downscaling and spatial interpolation to provide weather data inputs.
- Connecting with risk management analysis systems.
- Integrating more abiotic and biotic stresses.
- Cultivar level coefficients, variations and understanding cultivar adaptations.
- For mitigation, the models need to include N_20 and CO_2 emissions estimates.
- For improved crop breeding, need more complex genetic traits, and linkages to genes/markers.
- Generic comments included: better testing / evaluation, calibration, wider application of models, improvements in key processes.

WHAT ARE THE CONSTRAINTS TO DEVELOPMENT, APPLICATION AND GENERATION OF DESIRABLE OUTCOMES?

WHAT ARE THE MAIN STRENGTHS OF THE MODEL?

In identifying the constraints on model develop, it is worth exploring what respondents felt were the strengths of the models they were referring to, on the basis that perceptions of strength may indicate areas of weaknesses. The survey shows that out 213 responses (Figure 3) the '*detailed process representation*' was seen to be the main strength (60; 39%), but correspondingly only 18 (13%) saw the '*robustness in the quality of outputs*' as being the main strength, which was instead ranked as the 5th. The '*representation of process interactions*' was seen to be the second main strength (56; 34%). This indicates a potential paradox of the interest of modellers in developing models that are capable of detailed representation or process, but less in the need to produce outputs of a robust quality (and therefore higher utility in achieving desirable outcomes of model use) and influence policy development (see Figure 2). This potential paradox is also reflected by the '*skill in representing observed phenomena*' achieved the lowest ranking of model strengths.

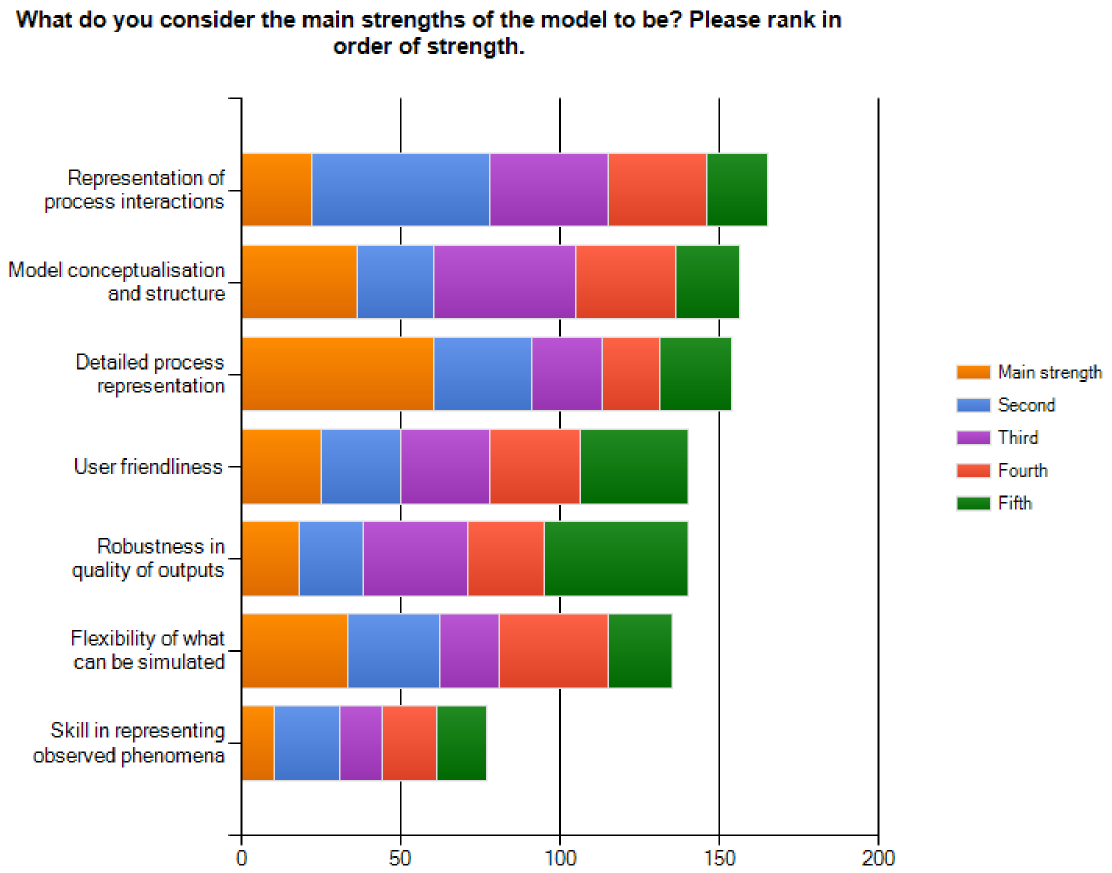

FIGURE 3 RESPONDENTS VIEWS ON THE MAIN STRENGTHS OF THE MODEL THEY ARE REFERRING TO.

Hence the models can be seen to be strong in methodology (representation of processes and their interactions), but not so much in the quality of outputs and representing observed phenomena. In reality these results are likely to be a reflection of the differing scale of model coverage (i.e. field vs. region / global), purpose and need for flexibility. However, literature on the evaluation of models indicates that the ability to represent observed phenomena (i.e. crop responses to weather variability) is a key aspect (i.e. Bellocchi *et al* 2009).

An alternative interpretation of the results may be that the responses reflect a large percentage view of reductionist scientists (due to those most likely to receive an invitation to participate in the survey), who's primary objective is to understand micros-scale processes, and hence have a less direct relationship with the wider spatial, temporal and macro-economic scales influencing the outcomes of model use.

Transferability of Models

All but two of the models detailed are transferable (can be applied in multiple locations), with no (27%) or minor (49%) re-parameterization (Figure 4). However, there have been issues (29%) on getting quality data to do so, including soil (11), yield (7), weather (5), and cultivar (5).

Specific comments on this issue included:

- Need to have calibration (particularly crop yield, water and soils) and input data including weather (particularly sparsely available solar radiation), soils and specific management for the new location.
- The need for these data will vary depending on the scale of model application.
- Format of data for new sites may not match those required by the model.
- Need for evidence of location specific evaluation.
- Need to determine if the location has extremes or unusual combinations of attributes that are beyond the scope of the model.

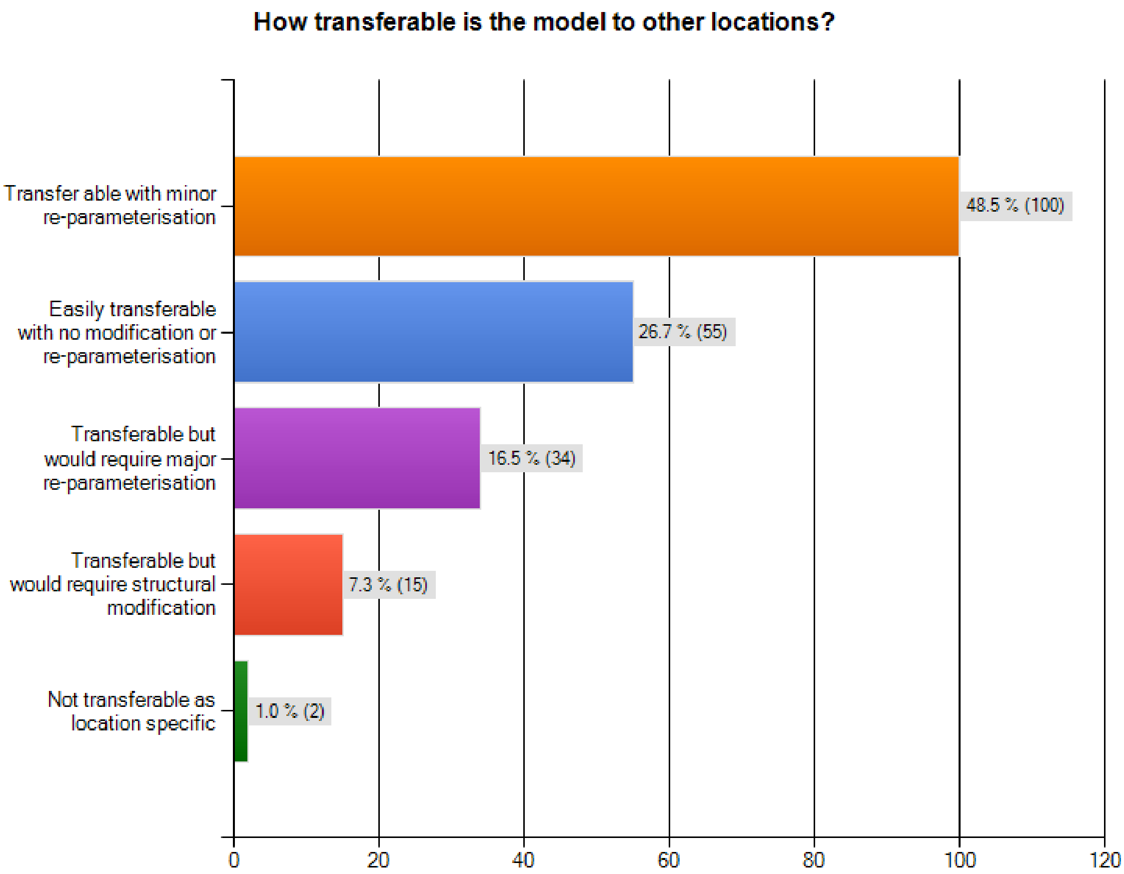

Figure 4 Transferability of models and level of effort required to apply the model in a new location.

GAPS IN MODELLING CAPABILITIES, APPLICATION AREAS AND CROPS REPRESENTED

CROPS REPRESENTED

Approximately 150 individual crops (including trees / forests) were specified in the survey (see Appendix 2). A total of 177 responses indicated the models used were for multiple crops (78%) and 51 were for single crops (22%). The major food crops were reported as being represented to some extent, ranging from the main cereals to vegetables, grasses, nuts and fruits. There were also models reported that represented tree growth, either for fruit or biomass, but it was unclear from the responses as to what extent these could be utilized for estimating foliage production for sylvo-pastoral systems.

ADDING NEW CROPS

Of 222 responses, 25 (11.3%) indicated that new crops could not be added to their models, but 162 (73.0%) said that they could, with a further 35 (15.8%) not knowing. Of those 162, 83 (51.2%) stated in respect of the effort required to add new crops, that '*no structural change* (needed) *but requires detailed calibration effort / addition of new parameters*' whilst 44 (27.2%) said that it '*requires model structural change, detailed calibration effort and new parameters*'. A further 35 (21.6%) said that it '*requires detailed calibration effort but no new parameters*'.

The main limitation to adding new crops was seen by 152 (77.2%) respondents (out of 197) to be '*data about the new crop*', whilst 32 (16.2%) said it was the '*model structure*'. Further comments highlighted the elements of resources required to add new crops (funding, time, staff required) and availability of data for calibration and testing purposes.

MODELS REPRESENTING OBSERVED VARIABILITY

When asked "Has the model been used to investigate responses to observed climate variability", from 140 responses 91 (65.0%) said yes, 26 (18.6%) said No, 23 (16.4%) said didn't know. Of those saying yes, 37 provided comments, which included:

- Details of testing the models' ability to represent climate variability at site specific and regional scales.
- Indications that precipitation variation influences yield the most.
- Variation between years was more common than within years.
- Use of the models for operational support.
- Used for research on production limitations due to weather variability.
- Responses in relation to Los Niños cycles.
- Spatial and temporal variations across climatic zones.
- Some reported variability in the skill of the model for crop and country combinations.

REPRESENTATION OF WEEDS, INSECT PESTS, PATHOGENS AND PHYSICAL DAMAGE

From 132 responses, the approaches to incorporating crop damage varied, with some models not having functions to represent effects of damage, whilst others are in the process of including damage functions (Figure 5). Those that did include damage functions can be summarized as:

- Incorporating external damage, but post simulation.
- User defined damage parameters / 'factors', but not always dynamic with weather and crop development.
- Yield gap parameter that reduces leaf area / or otherwise reduces the crops' ability to intercept solar radiation.
- Weed competition for resources.

- Dynamic pest interaction varying with temperature, relative humidity and residues. However comments on this level of detail indicated that there was a greater need to know when damage occurs and under what conditions to match modelling approaches with observed events.
- Representation of specific damage types, i.e. lodging, frost and flooding.
- Some individual crop pathogens were represented, i.e. *septoria tritici* in wheat.

Further indications from comments were towards the need to better integrate between the conditions that lead to insect pests and pathogen outbreaks with the state of crop development, and that an overall improvement in real yield estimates would be gained from dynamic (weather and soil conditions, crop status and specifics of each damage type). Other responses questioned whether it is possible to model the various types of crop damage due to the site-specific nature and farmer reactions to the damage type.

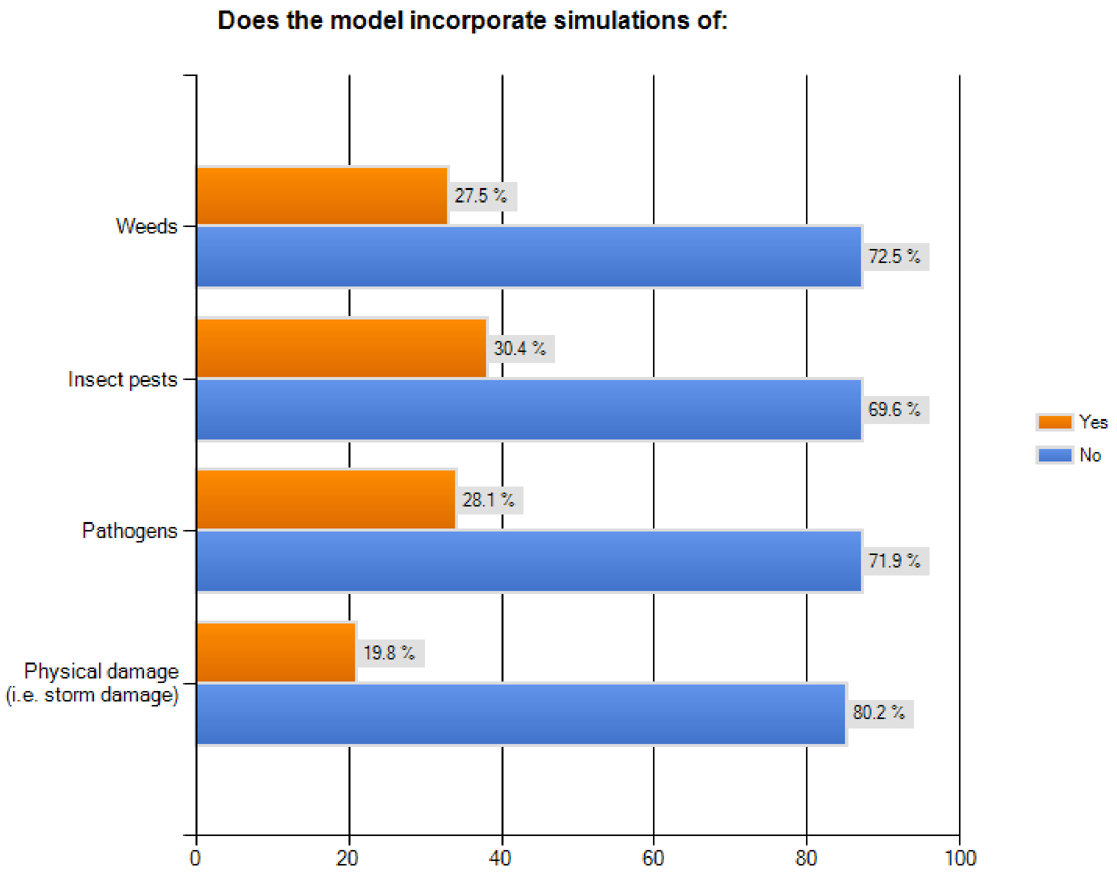

FIGURE 5 RESPONSES AS TO WHETHER THE MODEL INCORPORATES SIMULATIONS OF WEEDS, INSECT PESTS, PATHOGENS OR PHYSICAL DAMAGE

From 141 responses, 98 (69.5%) said that the model could be adapted to include pests, pathogens and physical damage effects, with only 14 (9.9%) stated that their model could not be adapted. Twenty nine (20.6%) did not know if the model they were reporting on could be adapted to include damage effects. Comments indicate that for those models that did not include representation of damage, there would need to be a substantial investment in developing new parameters and functionality and therefore code. Greater collaboration with scientists working in the fields of insect and pathogen population dynamics would be of benefit.

SKILLS REQUIRED TO OPERATE MODELS

For the question of "What skills are required to run the model", from 151 responses, the general view (62%) was that there is a requirement for general knowledge about crop growth and management, though some (10, 7%) required programming skills, whilst 5 (3%) were run by the developer only (Figure 6).

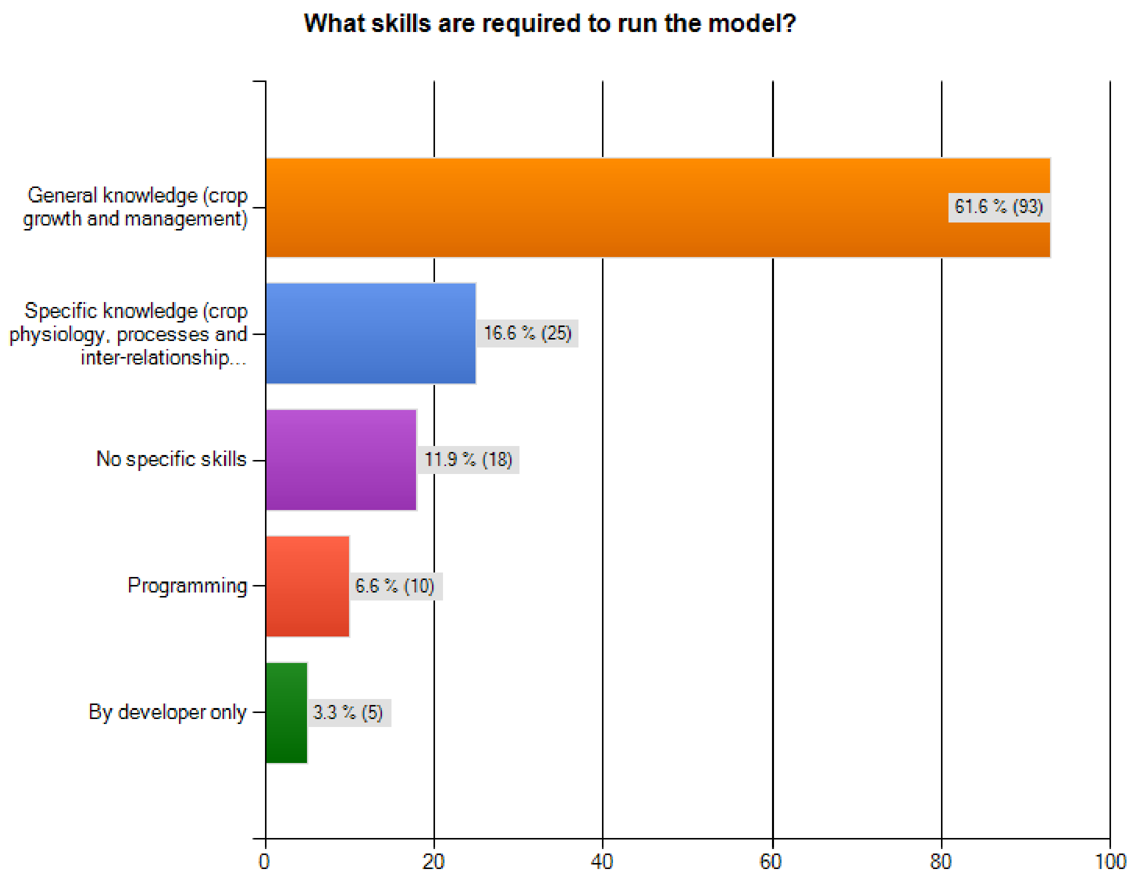

FIGURE 6 RESPONDENTS (151) VIEWS ON THE SKILLS REQUIRED TO RUN MODELS

COUNTRIES WHERE MODELLING HAS BEEN APPLIED

A total of 104 individual countries were reported as having had models applied within them, plus responses stating countries within continents (i.e. 'East African countries', 'Asia' 'Pacific countries' etc) and that modelling had been done at individual sites within countries (See Appendix 3 for a list of countries and counts of responses). Many responses stated the model being applied across the global / world (15). Several models have been applied in many countries, i.e. DSSAT has registered users in over 100 countries. Other models operate at the regional or continental scale and therefore include multiple countries. The format of the question and the types of responses has not made it possible to identify individual countries where no modelling has been conducted, but the results indicate that countries in the Middle East, Central Asia and Russian Federation areas are under-represented by crop modelling efforts.

From 216 responses, replying to the question 'Was the model developed for a specific location?, 155 (71.8%) said No, whilst 45 (20.8%) said Yes. A further 16 (7.4%) did not know.

GRASS MODELLING

From 274 responses, 167 (61%) said their models did not represent grass of have linkages to livestock production, but 107 (39%) said Yes. From these yes responses, 17 (20%) said their model was '*grass specific*', 49 (57%) said their model was '*Part of a wider range of crop representation*' and 20 (23%) said it was '*part of a decision support system*'.

For geographical coverage, 42 (51%) said their model represented both temperate and tropical grassland, 21 (26%) were for temperate only, and 8 (10%) for tropical grasslands. Comments indicated that representation varied from specific swards at a certain locations, to regional and global coverage, and that several models had been adapted for specific grass species.

GRASS SWARD COMPOSITION

For the question of "Is the model mono-species or mixed", from 76 responses, 36 (47%) said their models were for mono species, 10 (13%) were '*Limited mixed (i.e. mono-species grass and clover)*', another 10 (13%) were '*Mixed multiple species without inter-species competition*' and 20 (26%) were '*Mixed multiple species including inter-species competition*'.

REPRESENTATION OF GRAZING RESPONSES

From 79 responses, 38 (48%) said Yes, the model represents grazing responses, 26 (33%) said No, and 15 (19%) didn't know. Comments indicated a wider range in levels of detail included, from simple (specification of amount of herbage removed per day), to detailed (with pasture – livestock interactions in rotational grazing systems, nutrient cycling and feed quantities). From 81 responses, 26 (32%) said their models were linked to livestock systems models, 41 (51%) said they were not, and 14 (17%) didn't know.

MAIN PROCESSES

The development of grass modelling capabilities in relation to their most important processes shared common areas with general crop models (water use, light interception, nitrogen etc), but had additional requirements. These centre around the response of the plants to grazing and cutting, and the processes of translocation (biomass partitioning) of resources within the plant between below and above ground and interaction with grazing. Table 2 shows the results from responses stating the first and second most important modelled processes in grass models.

TABLE 2 MAIN TWO PROCESSES VIEWED AS MOST IMPORTANT WITHIN GRASS MODEL

Main process with grass model	**Main**	**Second**
Responses to Grazing / cutting	12	6
Translocation of resources within plant	5	4
Photosynthesis and biomass partitioning	4	2
Inter and intra specific competition	2	
Biomass pools corresponding to tissue age/quality classes & dynamics	1	
Biomass production driven by rain use efficiency	1	
Dry matter yield and ME content	1	
Environmental interaction	1	
Functional representation of plant growth and assimilate allocation between shoots and roots	1	
Growth and development	2	1
Light interception	1	
Light use conversion efficiency	1	
N uptake by the whole plant	1	1
Nitrate uptake of legumes	1	
Partitioning	1	
Perenniality and ability to store CHO and N for use in re-growth after dormancy/frost	1	
Phenology	1	
Resource capture (nutrient, water (rainfall or irrigation), solar radiation)	1	
Response to climate variables	1	
Simulation of leaf area & nitrogen dynamics as per crop models	1	
Soil C and N transfers - grass growth very simple	1	
Use of water		2
Abiotic and biotic stress factors		1
Carbon allocation		1
Death of plant under high water stress and restoration after return of rain		1
Digestibility & protein content of forage		1
Estimate sufficiency of resources for optimal production		1
Flexible re-growth after harvesting cycles, all the way to zero leaf area		1
Ratio shoot N:roots N		1
Root/shoot ratio dynamics in relation with herbage removal (grazing or harvest)		1
Senescence		1
Silage		1

The survey questioned downed to the sixth most important process, with responses reflecting the details of the first and second levels, plus:

- Responses to management (other than razing / cutting).
- Responses to trampling.
- Nutrient return through animal excreta.
- Effects of fire.
- Erosion.
- Legume N fixation and inter-species competition.
- Effects of selective grazing (animal and plants species selection).
- Dead plant material mineralization (related to senescence).

IMPROVING REPRESENTATION OF THESE MAIN GRASS PROCESSES

The majority (28 responses, 62%) viewed '*Targeted experimentation to give more specific calibration data*' as the most important to improve representation of the main processes in models simulating grass, couple with 19 (44%) stating a need for '*Greater flexibility in model to account for growth responses to management i.e. grazing or cutting*' (Figure 7).

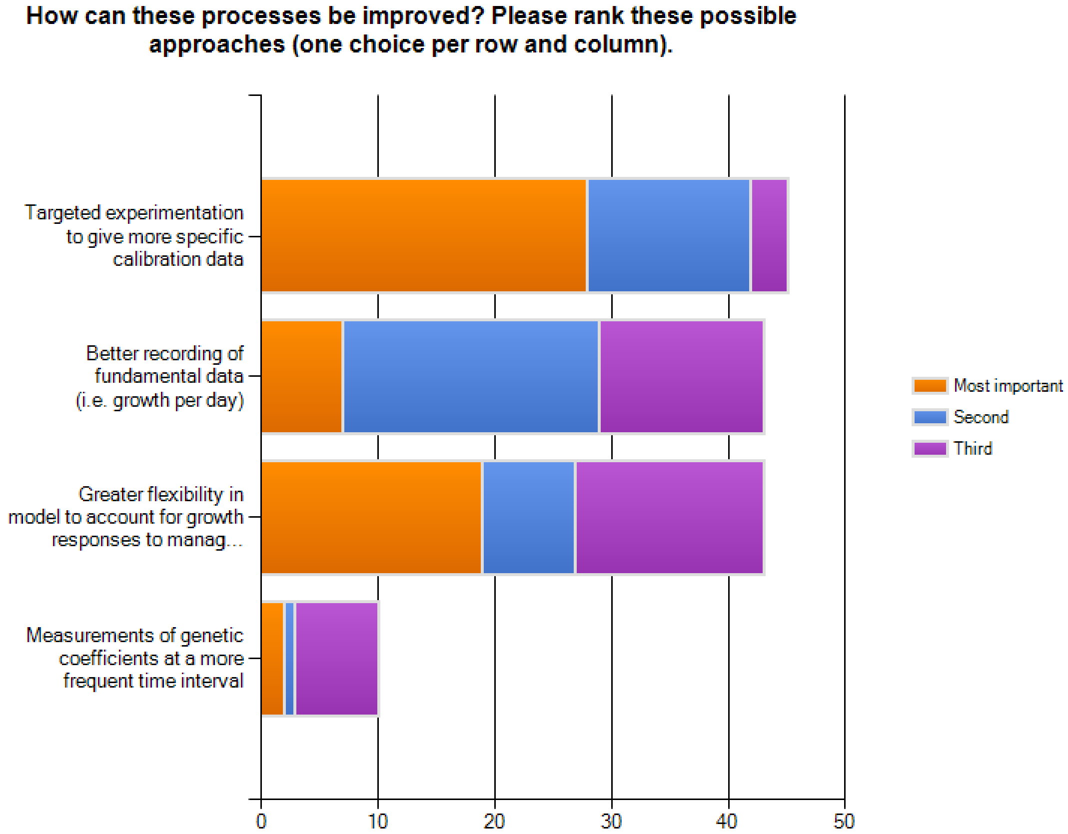

FIGURE 7 RESPONDENTS VIEWS ON HOW MAIN PROCESSES IN GRASS MODELS CAN BE IMPROVED

How can the crop modelling capabilities be improved?

This next section examines what the most important processes are in crop models and how they can be improved.

Modelled processes

Respondents indicated that the best way to improve modelling capabilities was to have more and better quality data for calibration and testing purposes. This data would come from more experimentation and detailed research into modelled processes (Figure 8). Improved mathematical representation, addition of new processes and more sophisticated evaluation methods were seen as less important.

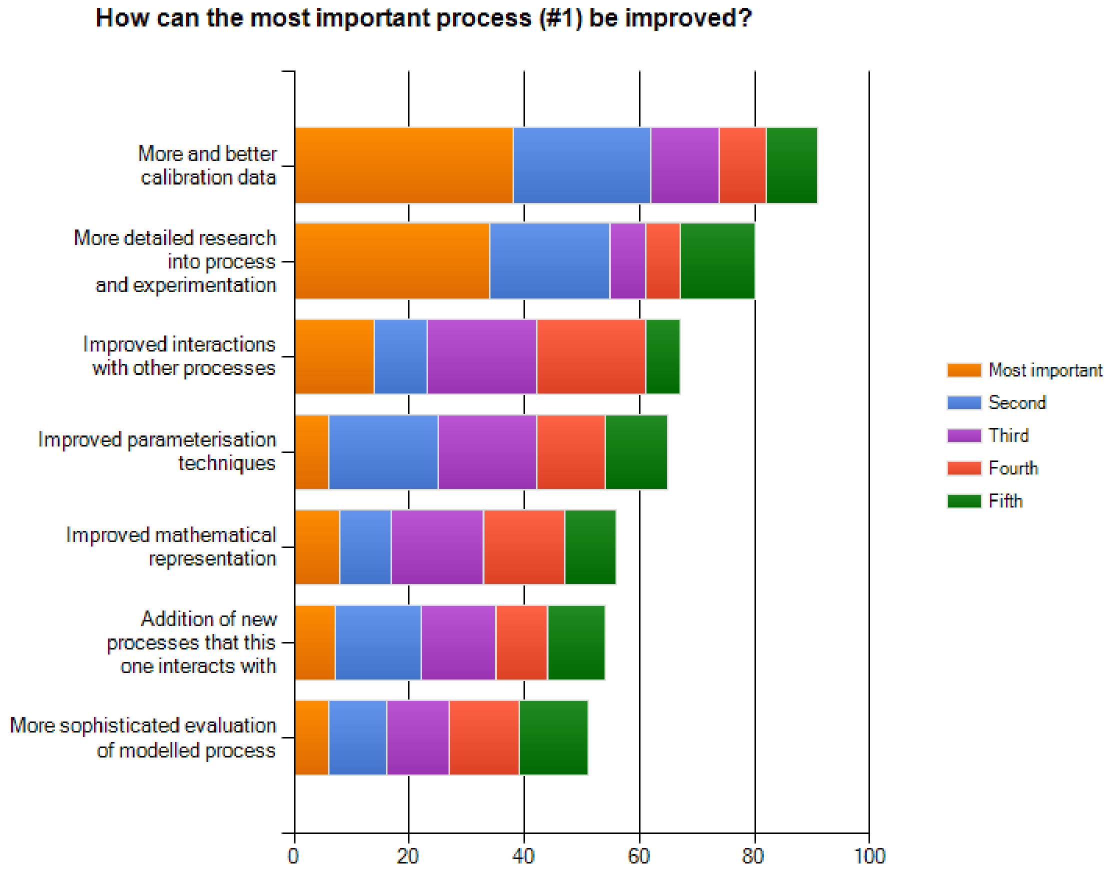

FIGURE 8 VIEWS ON HOW THE MOST IMPORTANT PROCESS WITHIN THE MODEL CAN BE IMPROVED (X AXIS IS THE COUNT OF INDIVIDUAL RESPONSES)

The most important processes identified included photosynthesis, carbon balance, water dynamics and crop development. Table 3 is an aggregation of the name / description for the processes detailed and the approximate number of responses.

TABLE 3 AGGREGATION OF RESPONDENTS' SPECIFICATION OF THE MOST IMPORTANT PROCESS WITHIN THEIR MODELS

Most important process, response count		Second most important process, response count	
Photosynthesis	17	Soil water balance	8
Carbon (balance, assimilation, cycle)	12	Crop development (phenology)	7
Crop development (phenology)	11	Nitrogen	5
Soil water balance	4	Assimilates storage and relocation	2
Yield	4	Carbon (balance, assimilation, cycle)	2
Canopy development	3	CO_2 enrichment	2
CO_2 enrichment	2	Heat stress effects	2
Impact of climate change on crops	2	Photosynthesis	2
Light interception	2	Respiration	2
Plant water	2	Abiotic stress	1
Response to variability / extremes	2	Abortion of flowers by extreme temperatures	1
Weather modules/ routines	2	Biomass accumulation	1
Biomass production	1	Carbohydrate production and balance	1
Climate-Plant Interactions	1	Dark respiration	1
Climatic variables	1	Dry matter production and partitioning	1
CO_2 versus TE, RUE & N stress	1	Dynamic carbon and nitrogen allocation	1
Competition for light and water	1	Framing adaptation strategies against climate change	1
Crop growth	1	GHG fluxes	1
Economic-ecological optimisation	1	GIS/spatial application	1
Energy partitioning	1	Inclusion of fertilisation in crop growth process	1
Extension networks	1	Insects	1
Feedback mechanisms	1	Interaction between soil and root anchorage	1
Generation of probabilistic entities and climate change outputs	1	Leaf area development	1
GHG emissions	1	Management interventions	1
Heat sensitivity of photosynthesis	1	Mineralization of soil N	1
Interaction between canopy and wind	1	Net primary production	1
Layered canopy model	1	Root development	1
Leaf cover area	1	Variation in pasture growth in response to climatic variation	1
Matching feed demand with feed supply	1	Within-plant transport	1
Natural disturbance	1		
Object oriented on vegetation improvement, vegetative protection of the climate,	1		
Overall representation of conditions that favour disease development	1		
Rainfall and temperature change	1		
Resource acquisition - light, water, nutrients	1		
Root system development	1		
Salinity stress	1		
Sink-source relationship for grain filling	1		
Soil C & N	1		
Stress response	1		
Tuber number	1		

For the processes listed as the second most important, responses on how their representation could be improved followed a similar pattern as for the most important process (Figure 8), with 49.1% stating that improvements would be achieved by 'more detailed research into process and experimentation, and 35.9% with 'more and better calibration data'. Responses for the third and fourth listed most important processes followed similar details and themes as for the first and second, as did the views on how these process representations could be improved.

Improvement in the quality of crop input data

For the question of "How can the improvement in crop input data be achieved" (Figure 9), from 108 responses, the most important way was seen to be a '*Greater effort in collecting fundamental crop growth data*' (27 as most important, total of 82), followed by '*Better shared data between research disciplines*' (28 as most important, total of 75) (Figure 9). Having '*common protocols for data collection*' was the largest second most important option (blue in Figure 9).

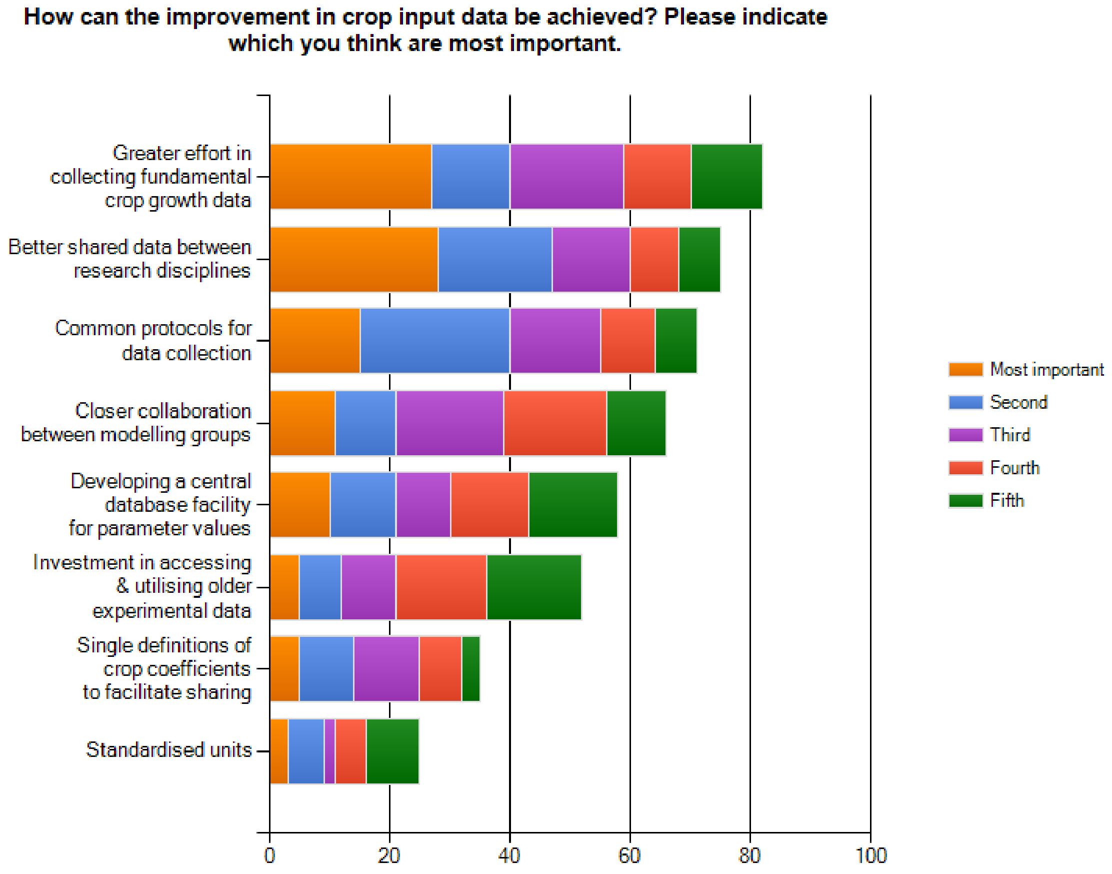

FIGURE 9 RESPONDENTS VIEWS ON HOW AN IMPROVEMENT IN CROP INPUT DATA COULD BE ACHIEVED

IMPROVEMENT IN THE QUALITY OF SOIL INPUT DATA

For the question of "How can the improvement in soil input data be achieved" (Figure 10), from 94 responses, as with the improvement of crop inputs, the majority of respondents saw '*Greater effort in collecting fundamental soils data*' as the most important (Figure 10). There was considerable interest (60 responses in total) for '*developing a central database facility for soil parameter values*'. The second most popular option (blue in Figure 10) was for investment in accessing and utilising older experimental data, though this option overall had only 37 responses in total.

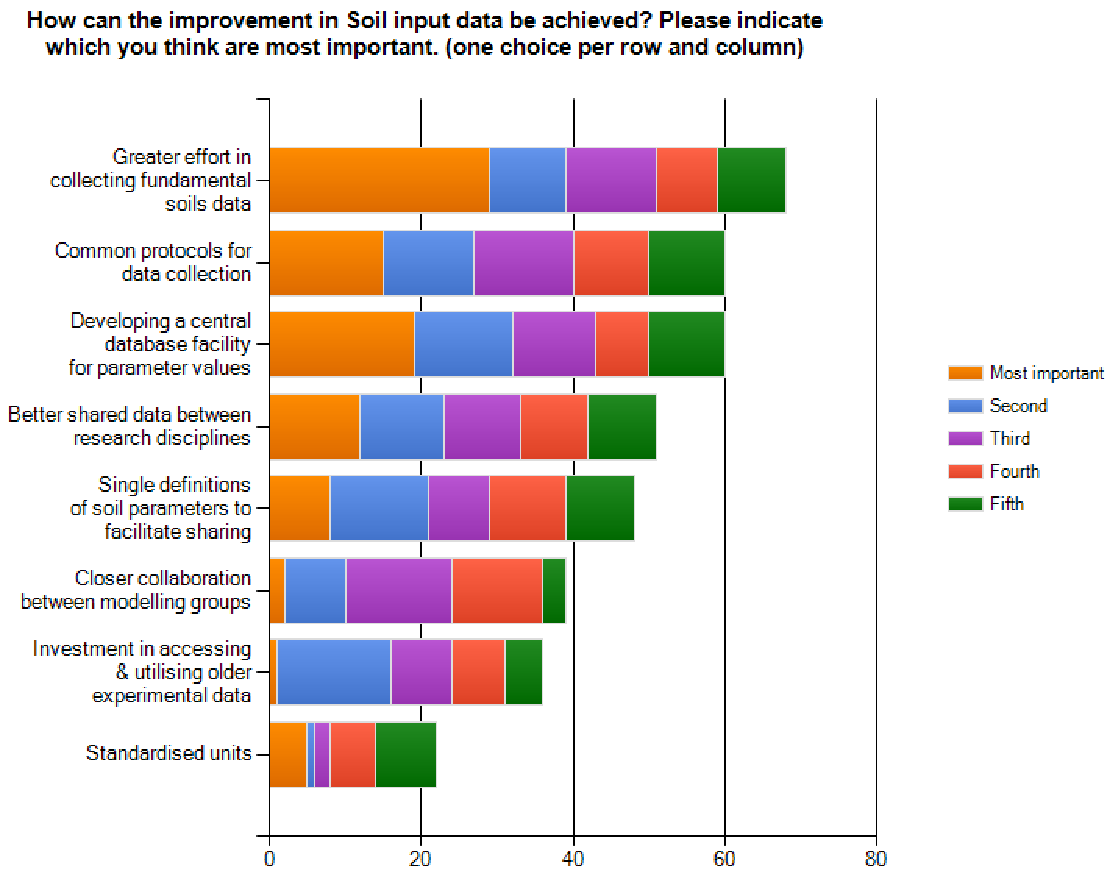

FIGURE 10 RESPONDENTS VIEWS ON HOW AN IMPROVEMENT IN SOIL INPUT DATA COULD BE ACHIEVED

Improvement in the quality of management input data

For the question of "How can the improvement in management input data be achieved" (Figure 11), from 79 responses, as with the improvement of crop and soil inputs, the majority of respondents saw '*Greater effort in collecting fundamental soils data*' as the most important, followed by '*Better shared data between research disciplines*' and '*Common protocols for data collection*'. Having '*common protocols for data collection*' was the largest second most important option (blue in Figure 11). *Closer collaboration with farmers* was also seen as an important way of improving management input data to the models.

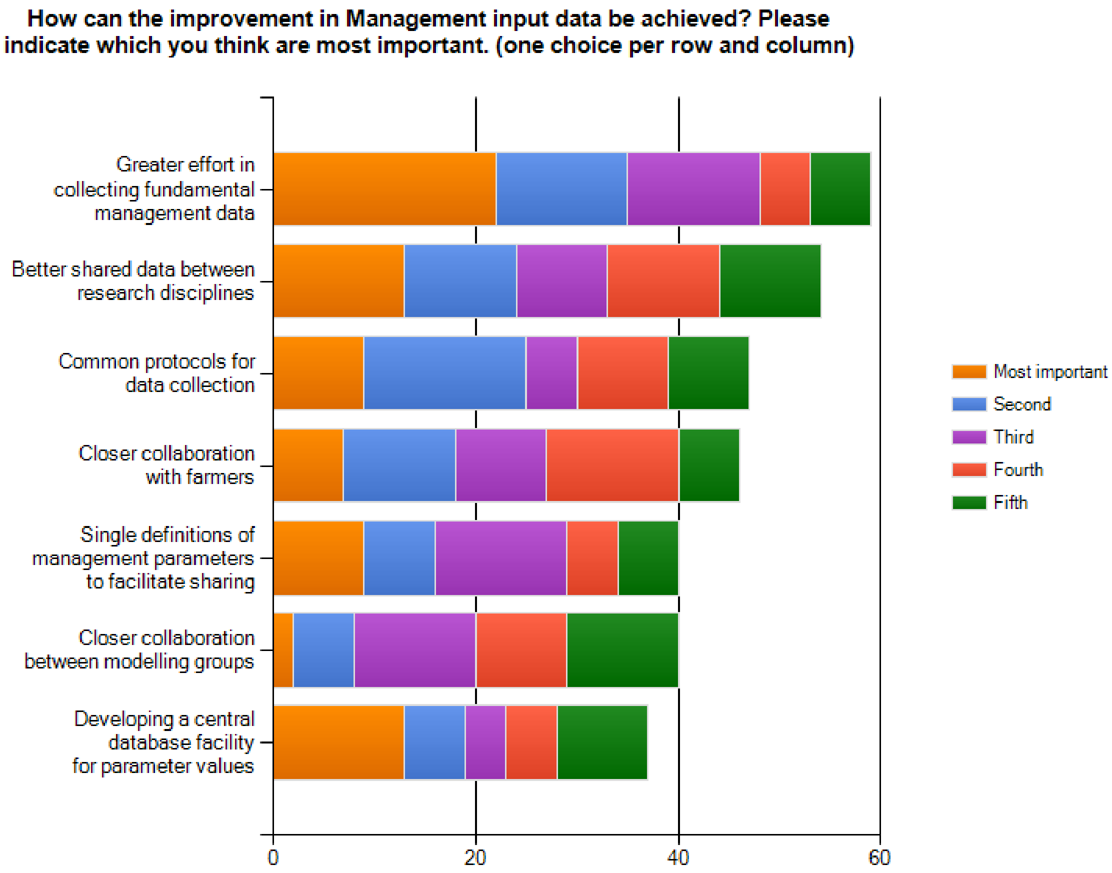

FIGURE 11 RESPONDENTS VIEWS ON HOW AN IMPROVEMENT IN MANAGEMENT INPUT DATA COULD BE ACHIEVED

Status and the improvement options for the water balance representation

For the question of "How is water movement represented within the model", from 122 responses, 67 (54%) said '*Crop + soil ET with detailed soil water balance*', 46 (38%) said '*Crop + soil ET with simple soil water balance*', whilst 5 (4%) said '*Crop transpiration only (no soil water balance)*' and 4 (3%) had '*Soil transpiration only*'.

The issue of available calibration data and its quality is again seen as the most important for improving models' representation of water. Some of the responses relate to other comments about the need for greater levels of interdisciplinary, here in respect of the need for better information that hydrologists may provide in respect of ground water and water table fluctuations.

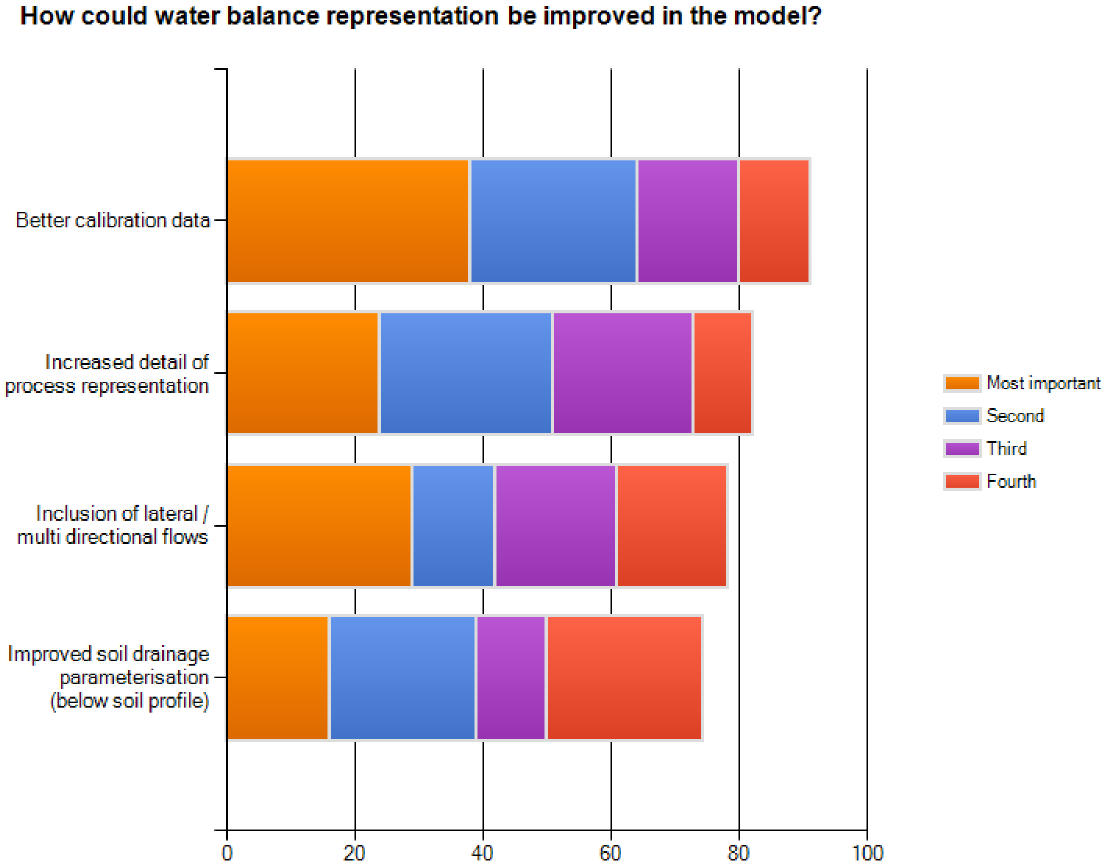

FIGURE 12 VIEWS ON HOW WATER BALANCE REPRESENTATION CAN BE IMPROVED

Suggested improvements in the models include:

- Improved representation of root growth and functions.
- Better inclusion of ground water and water table movements, particularly any upward flux.
- For adaptation uses, need to have full energy balance to predict conductance effects on foliage temperature.
- Below-ground profile is not enough, as there is a need for better ways to handle saturated conductivity within the root zone.

Improvement in the quality of input weather data

For the question of "How can improvement of the input weather data be best achieved to increase the quality of crop model outputs" (Figure 13), from 110 responses, the availability of weather data at a 'finer spatial scale of coverage' was seen to be the most important (total of 80, with 38 (48%) having this as their first option). Better interpolation techniques (between meteorological stations) (total of 74) and improved techniques for estimating missing data (70) were seen as the next two most important.

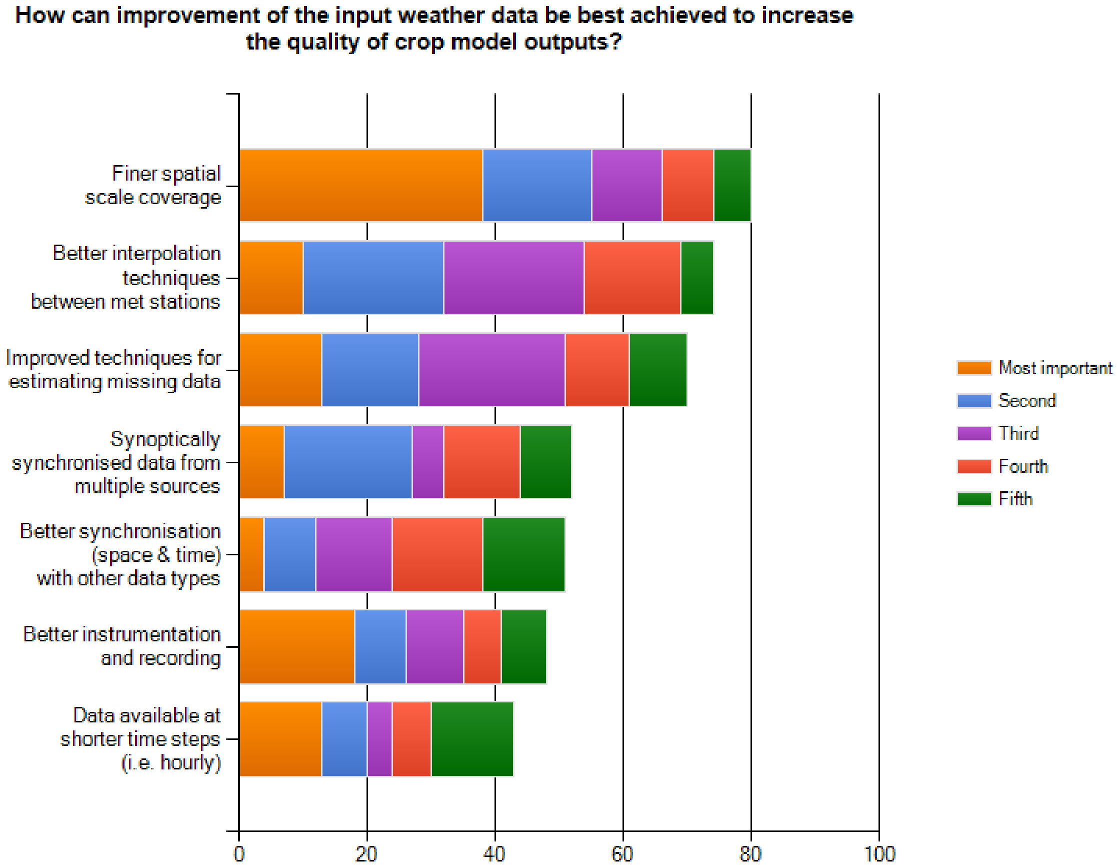

FIGURE 13 RESPONDENTS VIEWS ON HOW IMPROVEMENTS CAN BE MADE IN THE QUALITY OF INPUT WEATHER DATA

Model evaluation methods

For the question of "How do you think model testing can be improved" (Figure 14), from 100 responses '*better quality data for testing purposes*' (36 as most important, total of 67) was seen to be the most important, followed by '*Cross comparisons between models*' (8 as most important, 23 as second, total of 65) and a '*Wider range of outputs tested*' (17 as most important, 21 as second, total of 59). Comments highlighted the need for testing over multiple locations, management and climate variations.

From 101 responses, 30 viewed the testing effort as '*Sufficient to achieve acceptable quality of outputs*', 28 felt that testing was '*Limited by availability of suitable testing data*' whilst 24 said the test effort was '*Good but variable across range of model processes*'. A further 11 said the effort was '*Restricted (i.e. due to time and resource constraints)*', but conversely 8 said it was '*Good and at a consistent level across all model processes*'.

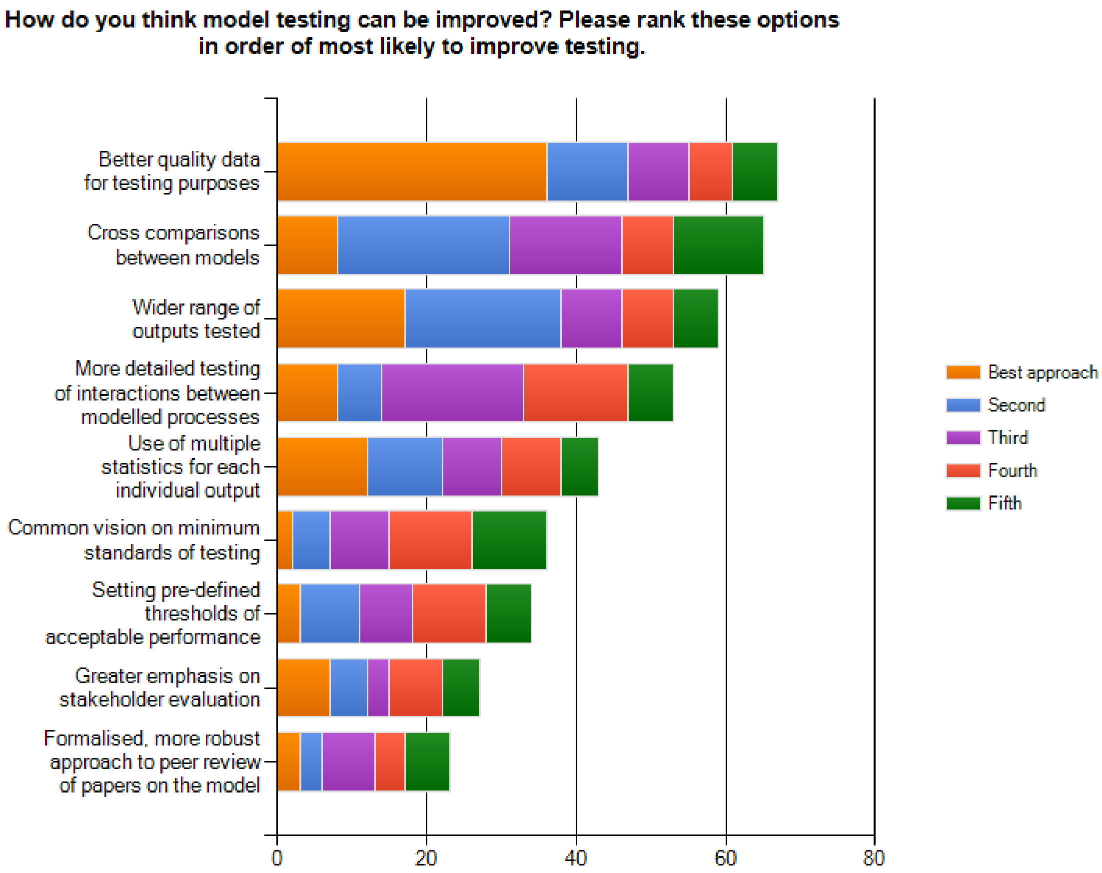

FIGURE 14 RESPONDENTS VIEWS ON HOW IMPROVEMENTS CAN BE MADE IN THE WAY MODELS ARE TESTED

On the role of calibration data, from 102 responses, 54 said the data was '*sufficient but limited*', 28 said it was '*adequate*', whilst 20 said it was '*limited*'. From 107 responses, 64 said that the model had been tested to assess its sensitivity to a range of input data quality, 20 said it had not, and 23 didn't know.

Simplification of the models

For the question of "Can the model be simplified (i.e. can the model be stripped down to an essential minimum set of process and still achieve its primary purpose)", from 138 responses, 63 (46%) said No, 47 (34%) said Yes, whilst 28 (20%) said Partially. Comments indicated that:

- Some models could be run with a reduced number of functions, or are modular so not all modules need to be run, or component based with each run separately.
- Simplification could be possible, but would depend on the purpose and level of detail, precision and accuracy required from the outputs.
- There were concerns that simplification would increase systematic errors.
- Several models were already considered to be simple enough.
- One model could be constrained in its spatial application (i.e. single field rather than multiple fields).
- Simplification may reduce capacity to represent interactions between processes.

Model documentation

In response to the question 'How well documented is the model?', from 149 responses, 47 (31.5%) felt that the model they were detailing had 'full documentation including interface instructions, detailed explanation of equations and process interactions' (most favourable option), whilst 34 (22.8%) said the documentation provided 'Guidelines plus some equations and explanations of process representation' (third most favourable option) and 24 (16.1%) went for the second most favourable option 'Guidelines including explanation of equations but limited on interactions between processes'. Five (3.4%) said the model was not documented, 22 (14.8%) said there was a 'Summary description' and 17 (11.4%) opted for 'Guidelines for operating model / user interface guide only'. These last three total 29.6% of responses, indicating that there is plenty of scope for improvement in the quality of model documentation. However the complexity of the model has not been considered in the appraisal of model documentation.

In respect of the question 'What are your views on the quality of the documentation?', from 143 responses, 49 (34.3%) went for the central option of 'Sufficient to use model and gain overview of processes', with only 28 (19.6%) going for the most favourable option of 'Well written explanations of use, detail and processes'. The same number of responses were gained for the second least favourable option of 'Adequate to use but insufficient to understand processes'. A further 16 (11.2%) said the documentation was 'Out of date and requiring detailed up-dating' (least favourable option), with only 12 (8.4%) going for the second most favourable option of 'Good level of detail on use, processes etc, but not clear'.

An interesting observation given in comments to the issue of model documentation was that user documentation may well be detailed and up to date, but model documentation tends to be scattered across multiple journal publications, implying that it is difficult to access a single source. Some comments pointed to the variability in documentation quality for a single model, with some user interface or model details being good whilst others were poor or missing. Other comments indicated that some models were still under initial development, or fairly new and documentation was still being prepared.

An overview of the responses is that there is a wide variation in the quality of documentation, and that there is scope for an all-round improvement. Several comments highlighted the difficulty, but need for maintaining documentation in parallel with code development.

Appendix 4 provides websites for models and documentation (where provided in the survey responses).

Publications on models

Respondents were asked to supply references and other publication details for the models they were reporting on. These can be found in Appendix 6.

General statements on model development requirements

For the question of "Considering crop models in general and their use in climate change research, what do you think are the main development requirements", there were 62 responses. These can be broadly summarised as:

- The need for basic data and reliable data sets, with ease of access, to support understanding of processes, calibration of parameters, testing and for input to models.
- Development and testing of model responses to extremes of rainfall and temperature.
- Better understanding on the role of elevated CO_2 concentrations and interactions with weather variables.
- Better representation of processes.
- Reduction in climate model projection uncertainty, including more appropriate spatial scales of representation.
- Inclusion of non-modelled factors such as weeds, pests and diseases.
- There was a mixed call for either greater simplicity of models or more detailed representation of processes.
- Need for more basic model outputs to indicate direction and severity of change, rather than comprehensive results, to develop adaptation options.
- Need for integration of a wider range of research disciplines and stakeholders, particularly closer collaboration with farmers and policy makers, but also plant genetists, soil microbiologists etc.
- Better representation of biotic and abiotic stresses.
- More rigorous testing methods, greater uncertainty evaluation and model inter-comparisons.
- More sensitivity testing to weather variability
- Need to shift towards modular structured, open source models, and / or a declarative modelling approach.
- Better connectivity between the scales of production / levels of organisation (plant, field, farm land use mix of enterprises and markets), including better crop-livestock systems.
- Back-up systems to ensure erroneous resulting from model misuse are identified and not used.
- More direct methods for linking crop models to climate models and running multiple climate scenarios enabling cross-scenario comparisons.
- Need for incentives for collaboration and better cooperation between researchers.

See also Appendix 5, which provides respondents views to the question: Considering crop models in general and their use in climate change research, what do you think are the main development requirements?

Climate Change and Crop Models

Model running mode

From 137 responses, 120 (87%) stated that their models were run separately ("offline") from climate models, though comments indicated that some models were in the process of being linked to climate models, and others that state that the model can be run either as an integrated part of a climate or independent

Climate projection data sources

For the question of "What spatial scale of climate model data has the crop model been used with? (i.e. scale of data inputs)", from 128 responses, 88 (68.8%) said they use site specific data, whilst 34 (26%) and 36 (28%) said they used GCM and RCM data, respectively. Other comments (20, 16%) detailed various sources of data, including multiple scales (GCM, RCM, downscaled) and 5 to 10km interpolated gridded data. Were site-specific data was used as input, 52 (51%) responses said they used a weather generator, and 42 (40%) used statistical methods.

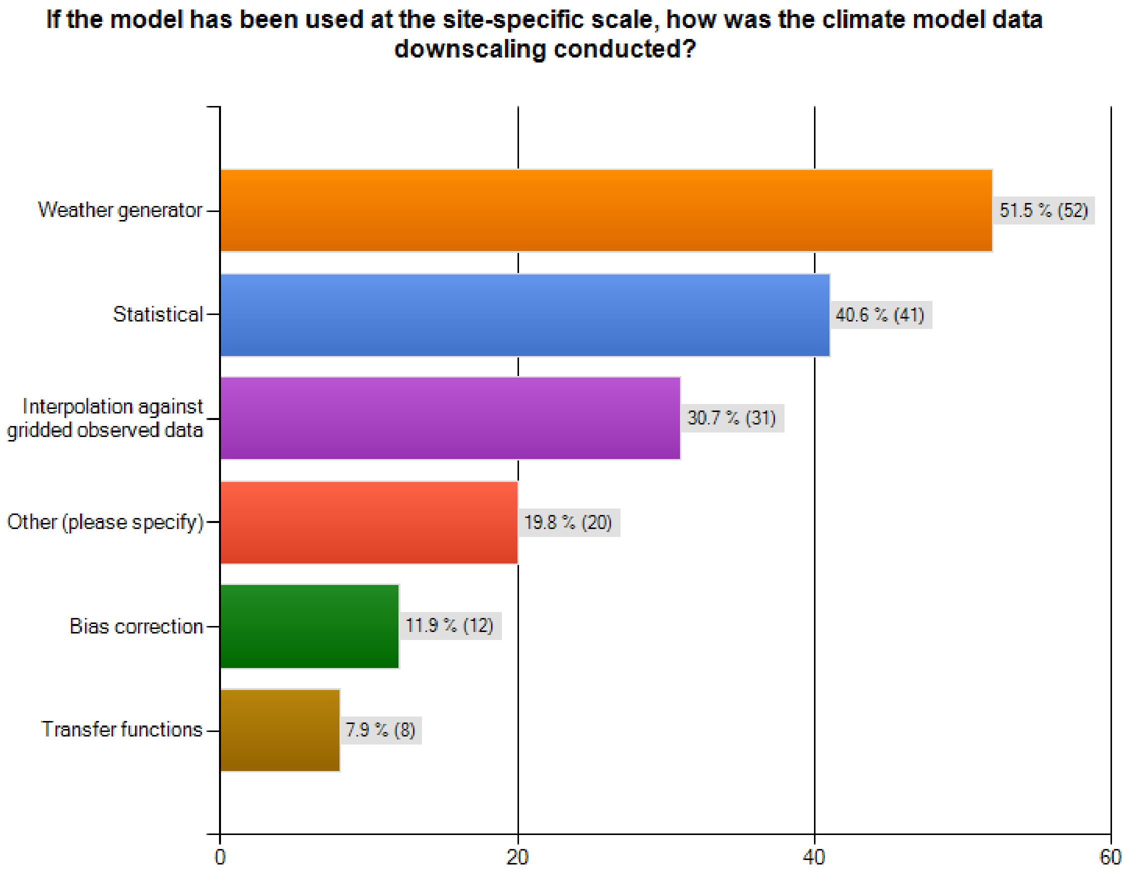

FIGURE 15 METHODS USED FOR DOWNSCALING CLIMATE MODEL DATA FOR USE IN CROP MODELS (X AXIS IS THE TOTAL NUMBER OF RESPONSES)

Specific comments on the issue of site specific climate projection data source included:

- GCM and RCM data not used due to lack of trust.
- Modification of weather data by multiplication by a constant (DSSAT).
- Some using multiple sources (ANR project Climator) or varying depending on user requirements.
- Some modellers using data provided by others researchers.

MODEL INCLUSION OF ATMOSPHERIC CO_2 CONCENTRATION EFFECTS

For the question of "Does the model include atmospheric CO_2 concentration effects", from 144 responses, 95 (66.0%) said Yes, 37 (25.7%) said No, whilst 12 (8.3%) didn't know. Comments indicate effects are represented mostly through changes in photosynthesis, light and water use efficiency parameter values.

CALIBRATION OF MODELS AGAINST ELEVATED CO_2 EXPERIMENTS

For the question of "Has the model been calibrated against elevated CO_2 experiments", from 137 responses, 50 (36.5%) said No, 46 (33.6%) said Yes, whilst 41 (29.9%) didn't know. The FACE experiments were the most common source of data for calibration.

MODEL USE IN MITIGATION STUDIES

From 138 responses, 54 (39.1%) said their models had not been used for mitigation studies, 44 (31.9%) had been, and 40 (29.0%) didn't know. Of those were models had been used for mitigation, some had been used for carbon sequestration research only, but not GHG emissions, whilst others consider CH_4 emissions from livestock systems, or nitrogen processes. From 129 responses, 50 (38.8%) reported that the models used did not produce estimates of GHG emissions.

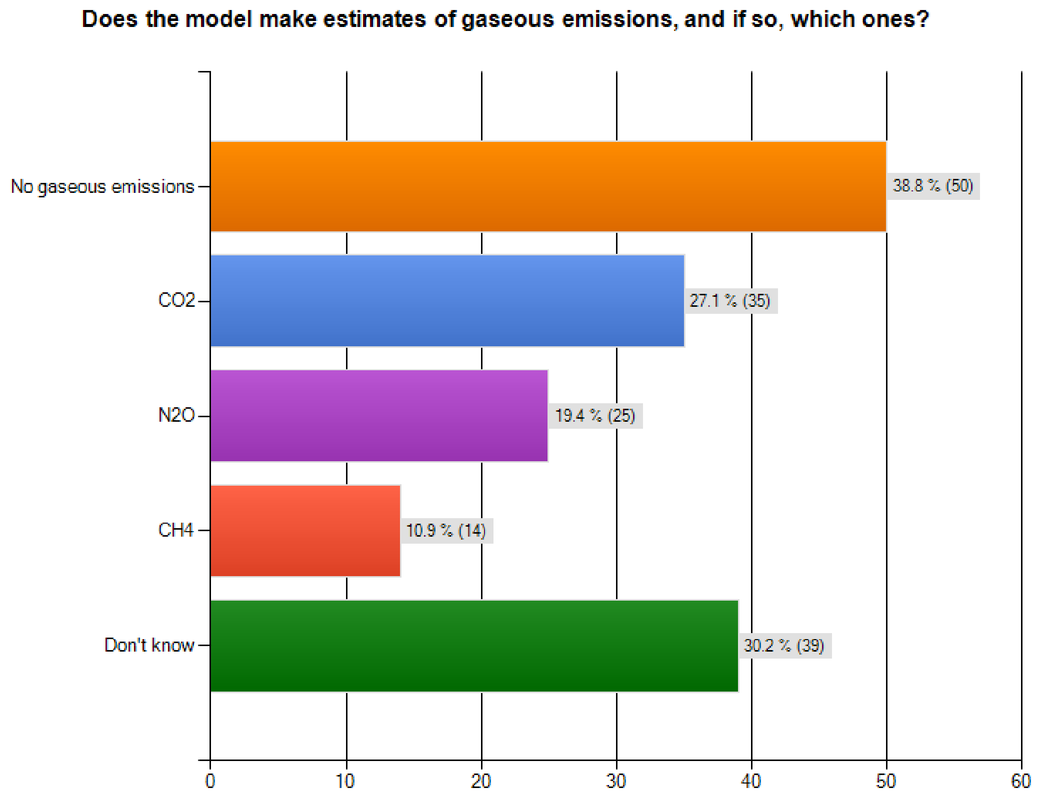

FIGURE 16 GASEOUS EMISSIONS FROM THE MODELS

MODEL USE IN ADAPTATION STUDIES

From 141 response on adaptation, 92 (65.2%) said Yes, the model had been used in adaptation research, 24 (17.0%) said No, and 25 (17.7%) didn't know. 51 (50.5%) respondents went on to say they used both variations in crop and management parameters, whilst 34 (33.7%) said they just varied management, and 10 (9.9%) varied just crop parameters. Comments indicated that adaptation options investigated centred around varying individual crop management operations (e.g., irrigation, fertilizer applications, and planting dates) and crop cultivar parameters. Others used alternate cropping patterns, changes in livestock stocking rates and livestock policies.

Links to livestock systems models and estimates of methane

From 71 respondents answering questions on whether their models represented grass, 41 (58%) said the models did not make estimates of methane production, but 9 (13%) said they did.

Use of models in ozone related research

For the question of "Can the model been used in ozone related studies", from the 135 responses, 66 (48.9%) said No, 10 (7.4%) said Yes, and 59 (43.7%) didn't know. Comments included:

- The effects of ozone would need to be added externally via the effects on processes and state variables that are built into the pest damage module.
- Would need to create new code to modify the photosynthesis module, i.e., create damage to leaf and affect stomatal conductance.
- Version of natural vegetation that accounts for O_3 stress exists.
- Others indicated that the models could be developed to include ozone factors, either has direct changes to the model (requiring substantial efforts in code and structural development), or external inputs.

Climate analogue potential for models

For the question of "Has the model been tested in ways that would enable analogue comparisons with potential future climatic conditions, and how", from 133 responses, 49 (36.8%) said yes, 37 (27.8%) said No, whilst 47 (35.3%) didn't know. Comments indicated that if the models had not already been used in analogue studies, then they had the potential to do so, and some were in the process. Others flagged the need for data to characterise the analogues sites, and that with a sufficient number of sites, some interpolation of results between sites may be possible.

Model development

State of development of the model

From 132 responses, 67 (50%) were defined as '*Recently developed code using modern programming language(s)*', 46 (34%) as '*Older model code developed over time and continuing to be evolved*', 15 as '*Exists as equations and description but not as software*', whilst 4 (3%) were '*Older software code no longer developed or supported*'.

Further developments for models

From 123 responses, 75 (61.0%) said Yes, further developments are planned, with only 6 (4.9%) saying No, but 42 (34.1%) didn't know. There were c. 40 additional comments providing good insights into the details of specific planned developments. These can be summarised as:

- Further calibration against observed data and parameterisation.
- Adding functionality, including new capabilities.
- Coupling with climate models, linking to GIS platforms.
- Improving sub-models.
- Including GHG emissions.
- Re-coding for open source development.
- Testing and sensitivity analysis.
- Genetics and plant breeding support.

An interesting observation here is that none explicitly mentioned plans for integrating with other research disciplines outside of the general realm of agriculture (i.e. socio-economics, participatory approaches etc) or linking to issues of energy use and sustainability.

Factors limiting further development

Not surprisingly funding was identified as the main limiting factor (72, 67.3%) in further developments of models from the 107 respondents (Figure 17). In line with previous results, calibration data was also seen as a key limiting factor (51, 47.7%), closely followed by our understanding of processes (43, 40.2%). It seems safe to assumed that the 45 (42.1%) of respondents indicating 'staff' as a main limiting factor were referring to the shortages of them (so related to funding), rather than their quality (though one comment indicated the need for more 'good modellers').

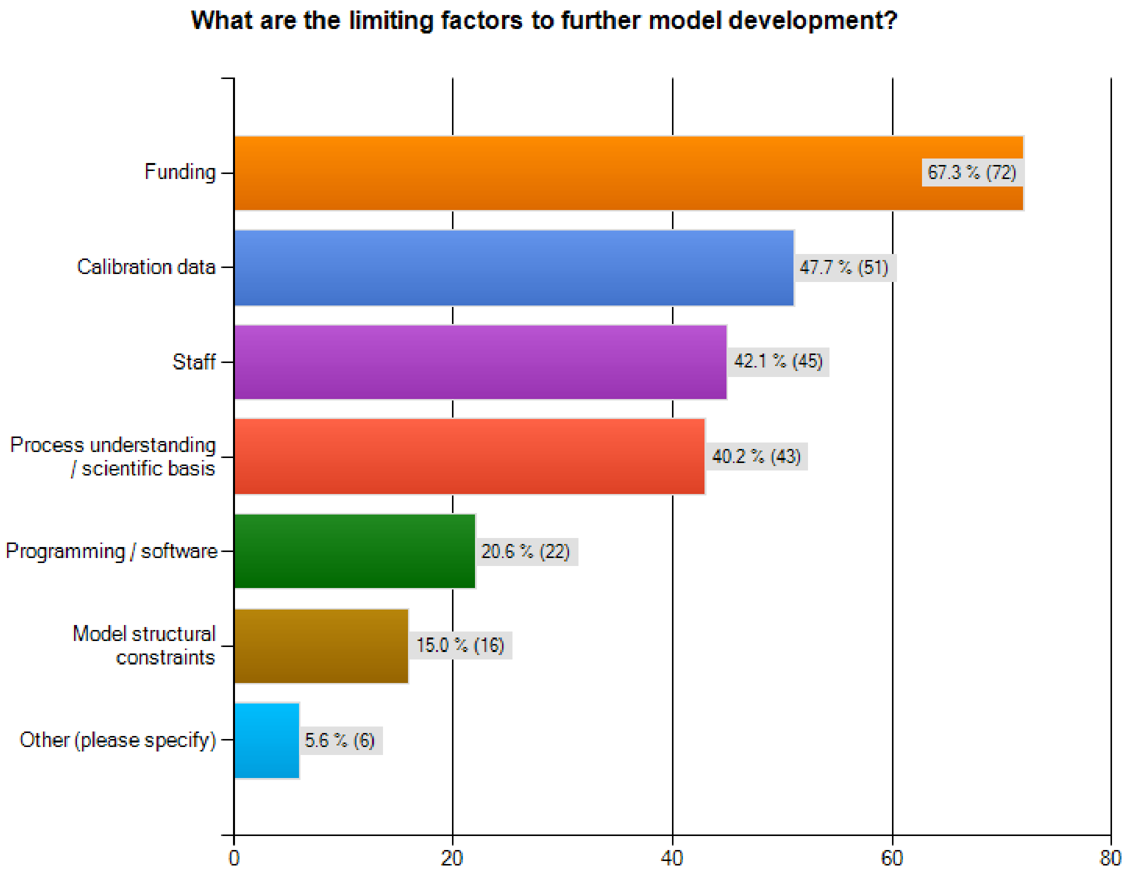

FIGURE 17 RESPONDENT'S VIEWS ON THE FACTORS LIMITING FURTHER DEVELOPMENT OF THEIR MODELS

FURTHER DETAILS ON DEVELOPING THE MODELS

At the end of the survey, respondents were asked to write comments on how crop models could be improved to enable better climate change and food security research. There were 62 comments made. The full set of unedited comments are available in Appendix 5. These serve as useful additions to and expansions of the points raised elsewhere in this report. The underlying messages is that the models need to be able to respond appropriately to the weather and atmospheric conditions that an altered climate will produce; that is, extremes, changes to mean conditions and ranges of variability.

REFERENCES

Bellocchi, G., Rivington, M., Donatelli, M. and Matthews, K. (2009). Validation of biophysical models: issues and methodologies. A review. *Journal of Agronomy for Sustainable Development* **30**, 109-130.

APPENDICES

1. MODELS REPORTED BY RESPONDENTS AND NUMBER OF RESPONDENTS PER MODEL

Model and number of responses							
AFRCWHEAT	1	Cropping Systems Model	3	JULES-CROP	2	SOAP	1
AgPasture	1	CropSyst	6	LCA models, tailored for each study	1	Soil Water Assessment Tool (SWAT)	1
Agro-BGC	1	Cropwat	2	Lodging model	1	Solanum	1
Agrodiversity	1	DETTOF	1	LPJmL	1	SPACSYS	2
AgroHydroLogos	1	DNDC	2	LUMOCAP	1	SPASS	1
Agrometshell	2	DRAINMOD, DRAINMOD-NII	1	MaxEnt	2	Specware 900	1
AmaizeN	1	DSSAT	72	MCWLA	1	Spreadsheet based models	1
Animal Model	2	ECOCROP	1	Mélodie (using STICS as a sub-model)	1	STICS	3
APES	1	EPIC	6	Modelo de Simulacion del Potencial Ecologico de los Cultivos	1	STOTRASIM	1
APSIM	17	Epidem_EGY	1	NUANCES-FARMSIM	1	Sundial / MAGEC / ECOSSE	1
Aquacrop	5	FAO climate change agricultural impact assessment toolbox	1	Oryza	1	SWAP	1
ArchiW	1	FLEOM	1	ORYZA2000	2	SWAT	2
Ausfarm	1	Fractional recovery	1	Panoramix	1	SWB Irrigation model	2
Ausgrow, Amangrow	1	GECROS	1	PASIM	1	Tropical Soil Quality Model	1
Broom's Barn Sugar Beet Growth Model	1	GIS models	1	People and Landscape model (PALM)	1	TsuBiMo	1
CAF2007	1	GISAREG	1	Potato Calculator	1	Tutu Adaptation	1
Canegro	2	GLAM	3	PROMET-V, Biological, Danubia	1	UK_DNDC	1
CERES models	3	Globio	1	RATP	1	Vegetation Interface Model (VIP)	1
C-Farm	1	Grass to Gas Model	1	Reifeprognose Silomais	1	Watermod	1
CGMS / Wofost	1	GRAZPLAN	1	RicePSM, RiceDevA,RiceWCA, RiceID, TomSim, TomDat, RiceSSWeb	1	WETMANSIM	1
Citrus Black spot	1	Groundnut improvement	1	SARRAH (Système d'Analyse des Risques Agroclimatiques, Habillé)	1	WheatGrow	1
CLIMEX Model for fusarium head blight	1	Hurley Pasture Model. Edinburgh Forest Model	1	Sfarmmod	1	Wheatmodel	1
Community networking	1	Hybrid Maize	2	SimAmazonia/Dinamica EGO	1	WOFOST	4
COMPETE	1	Impact model	1	SIMCAS	1		
COTONS and COTONSIMBAD	1	INFOCROP	5	Simile (note: modelling *software*, not a model)	1		
Crop planning models based on portfolio theory & loss function	1	Information Theory Process Network Model	1	SIMSDAIRY	1		
CROPGRO	2	Integrated crop livestock production system	1	Sirius	1		

2. CROPS (LAND USES) REPORTED IN THE SURVEY

Aeroids
Alfalfa
Altai wildrye
Annual ryegrass
Apples
Aqua crop
Aroids
Bahia grass
Bambara
Bambatsi
Banana
Bell pepper
Bermuda grass
Brachiaria
Broccoli
Bry bean
Butterfly Pea
Cabbage
Canola
Carrot
Cassava
Casupro
CAULIFLOWER
Cenchrus ciliaris
Centro
Chickpea
Chicory
Citrus
Clover
Coconut
Cocoyam
Coffee
Cold-season grass
Conifer forests
Forests - natural.
Cotton
Cowpea
Cucumber
Dry bean
Durum wheat
Deciduous forests
Egyptian Clover
Eucaliptus
Faba bean
Fallow
Fibre crops
Field peas
Finger Millet
Flax
Flowers
Forage crops
French Beans
Fruits
Garlic
Grass and clover
Grasses (general)
Green bean
Groundnut (peanut)
Haricot beans
Horsegram
Kava
Kikuyu
Lablab
Leek
Legumes
Lentil
Lettuce
Leymus chinensus (grass)
Lucerne (Alfafa)
Lupins
Maize
Mangoes
Millet
Mucuna (velvet bean)
Mungbean
Mustard
Native pasture
Nuts
Oats
Oil pumpkin
Navybean
Oilseeds
Olives
Onions
Indian Fig
Guinea grass
Paspalum (grass)
Pea
Peach
Pear
Pearl millet
Peas
Peatland vegetation
Pepper
Phalaris (grass)
Phaseolus bean
Pigeon pea
Pineapple
Poplar Tree
Potato
Pulses
Quinoa
Rapeseeds
Rice
Rough Grazing
Ryegrass
Safflower
Wetland habitat
Sesame
Set-aside
Soft wheat
Sorghum
Soyabeans
Spelt
Spring barley
Spring wheat
Stone fruit
Subterranean clover
Sugar cane
Sunflower
Sugar beet
Sweet potato
Sweetcorn
Tanier
Taro
Tef
Temperate forage grass
Tja
Tobacco
Tomato
Tree Crops
Tropical fruit trees
Tropical Native pastures
Tubers
Tulip
Upland rice
Value added Forestry products
Velvet bean
Vine yards
Walnut tree
Warm-season grass
Weeds
Weeds community
Wheatgrasses
Willow
Winter Barley
Winter pea
Winter rapeseed
Winter wheat
Yam
Zea mexicana

3. Countries where modelling was reported.

Country	Count	Country	Count	Country	Count	Country	Count
Afghanistan	1	Egypt	4	Malawi	1	Slovenia	1
Africa	10	England	2	Malaysia	1	South Africa	12
Algeria	2	Ethiopia	3	Mali	3	South East Asia	2
Argentina	11	Ethiopia		Morocco	1	Southern Europe	2
Asia	5	Ethiopia		Mauritius	2	Spain	9
Australia	25	Europe	2	Mexico	9	Sri Lanka	1
Austria	1	Europe	17	Morocco	4	Sudan	1
Bangladesh	1	Fiji Islands	1	Mozambique	2	Swaziland	2
Belgium	1	France	13	Nepal	1	Sweden	1
Benin	2	Germany	10	Netherlands	8	Switzerland	1
Bolivia	2	Ghana	6	New York, US	1	Syria	1
Brazil	19	Greece	2	New Zealand	10	Tajikistan	1
Bulgaria	1	Guatemala	1	Nicaragua	1	Tanzania	3
Burkina Faso	3	India	30	Niger	1	Thailand	8
Cambodia	1	Indian subcontinent	1	Nigeria	5	Togo	1
Cameroon	3	Indonesia	5	North Africa	1	Tunisia	2
Canada	13	Iran	5	Northern Iraq	1	Turkey	1
Caribbean Islands (experimental)	1	Iraq	1	Pacific countries	1	Uganda	1
Central US	1	Ireland	1	Pacific Islands (eg Fiji)	1	UK	16
Chiapas, Mexico	1	Italy	5	Pakistan	2	United States	54
Chile	5	Japan	4	Paraguay	2	Uruguay	6

China	21	Jordan	1	Peru	5	Uzbekistan	2
Colombia	8	Kenya	6	Philippines	5	Venezuela	5
Continental							
(Europe, Africa)	1	Korea	1	Poland	1	Vietnam	3
Costa Rica	2	Kyrgyzstan	1	Portugal	1	West Africa	3
Cote d'Ivoire	1	Laos	1	Romania	1	World	16
Cuba	2	Latin US	1	Saudi Arabia	1	Zaire	1
Cuba		Lithuania	1	Scandinavia	3	Zimbabwe	3
Ecuador	3	Libya	1	Senegal	1		

4. Model documentation websites

Model	Documentation website
AgPasture	http://www.apsim.info (to be uploaded)
AgroMetShell (AMS)	http://www.fao.org/nr/climpag/aw_3_en.asp
APES	http://www.apesimulator.it/help.aspx
APSIM	http://www.apsim.info http://www.apsim.info/Wiki/APSIM-Documentation.ashx http://groups.google.com.au/group/apsim
Aquacrop	http://wwww.fao.org
C-Farm	http://www.brc.tamus.edu/media/20536/overview%20of%20c-farm%20dec%202008%20web%20%20document.pdf
CGMS / Wofost	http://www.supit.net http://www.wofost.wur.nl
CLIMEX Model for fusarium head blight	http://www.hearne.com.au/products/climex/attachments/
CropSyst	http://www.bsye.wsu.edu/cropsyst
CSM	http://www.icasa.net/dssat/dssat45.html
DETTOF	http://www-ai.ijs.si/MarkoBohanec/dexi.html
DSSAT	http://www.icasa.net/dssat/

ECOCROP	http://www.diva-gis.org
EPIC	http://www.ars.usda.gov/Research/docs.htm?docid=9791 http://winepic.brc.tamus.edu/ http://epicapex.brc.tamus.edu/
GISAREG	http://www.wademed.net/Articles/205Campos.pdf
GLAM	https://www.see.leeds.ac.uk/redmine/public/projects/glam
Hurley Pasture Model. Edinburgh Forest Model	http://www.ceh.ac.uk
Hybrid Maize	http://www.hybridmaize.unl.edu/
JULES-crop	http://www.jchmr.org/jules/
LPJmL	http://www.pik-potsdam.de/lpj
LUMOCAP	Documentation is included in the system, but can also be made available upon request (hvdelden@riks.nl)
ORYZA2000	http://www.knowledgebank.irri.org/oryza2000/ http://www.knowledgebank.irri.org/oryza2000/default.htm#Oryza_User_Manual/6_-_Soil_-_water_balance/6.2.3.htm
People and Landscape model (PALM)	http://www.macaulay.ac.uk/PALM/
Soil Water Assessment Tool (SWAT)	http://www.swatmodel.tamu.edu/
Sundial / MAGEC / ECOSSE	http://www.abdn.ac.uk/biologicalsci/staff/details/jo.smith

WOFOST (Simple model adapted for PCRASTER)	http://www.wofost.wur.nl/

5. Respondents' Comments on main model development requirements

Question: Considering crop models in general and their use in climate change research, what do you think are the main development requirements? Please use this space to comment on how crop models can best be developed to enable better climate change and food security research.

NOTE: These are the unedited comments from the responses to the above question.

1. 1. Fine tuning the temperature thresholds for key physiological processes
   2. understanding the individual and interactional influence of various climatic factors on key processes like soil erosion, soil water availability, nutrient loss, uptake, source-sink balance, etc.
2. Best use of available resources (sensor development[crop, climate], Best methods for soil analysis, increasing resolution in the time and spatial domain), effort on common standard and interoperability, emphasize of involvement of users in evaluation and implementation of tools for decision making.
3. They need to respond to climate change (i.e., temperature, rainfall, CO2, humidity, wind) AND to management options that might be used to adapt to climate change. It is not enough to assume that the only adaptation mechanisms that farmers will use are to change planting dates and current varieties. there are many more adaptation options available to farmers...
4. The models should have C, N, and water balance. They should be responsive to temperature and CO2 and tested against metadata on these environmental drivers. The models need to predict realistic production, and that means somehow accounting for those fertility limitations found in developing countries.
5. There is need to develop robust and simple processes based dynamic crop growth models which can predict the impact of current climatic variability, future climate, soil, and management practices on the crop growth, yield and soil health both under well managed irrigated and poorly managed rainfed conditions across the world. The models need to predict crop growth and yield in response to above factors at regional scale. There is need to link crop growth models with GSMs and RCMs so that data generated through these models can be directly incorporated in crop growth models. These crop growth models need to be calibrated and validated at regional scale rather than location/point specific calibration/validation done currently. This could be achieved by better collaboration among the scientific communities working on these aspects across the globe and by better exchange of data/information among the modelling groups.
6. reliable datasets, access to good experimental data
7. 1) Crop models must be well calibrated for large spatial areas, under different farming systems and under different agro-ecological regions.
   2) In developing countries, main baseline must be the livelihood approach.
   3) Improve synergy with other crop data producers (i.e. statistics)
   4) Improve the use of remote sensing imagery.
8. MIPs and more - the community would, I believe, greatly benefit from moving away from 'black box' thinking, whereby crop science knowledge is believed to be contained within models, and towards a focus on interpretation, synergies between models, and an appreciation of the strengths and weaknesses of each model.
9. Uncertainty of parameters - primarily the ability to communicate that uncertainty to stakeholders.
10. more integration with GCM outputs.
11. They need some basic data about the behaviour of crops in environments with higher CO2 and temperature.
12. Understanding the way farm systems can be manipulated by farmers.
13. The ability to of the models to assist in addressing the challenge of climate change is just emerging and the capacity of the model is being developed. I think their use is limited to a few researchers. Models need to attract other users to help them in day to day matters and use as research and management tools.
14. Integration of crop models with climate models.
    Quantifying CO2, methane, N2O gases from agroecosystems
    Determining how increased temperatures and water stress affect reproductive processes in the field scale (not growth chambers).

15. The challenge is to make simpler yet more accurate models. THere needs to be new principle to represent the processes.
16. Assume that climate change is cyclical and not catastrophic.
17. Interactions between high temperatures and high CO_2 need to be better addressed.
18. Provide a basic output rather than a very complicated or comprehensive set of results. Everything under the context of climate change is merely a forecast. So, we need to keep focus in informing the direction and the severity of the changes, rather than focusing on detailing each process. We surely need to detect vulnerable areas and develop adequate adaptation strategies, then go to the field and test them, and have them ready for use, or start transferring them to farmers.
19. Crop models need to be linked to their use.
    Need a model that coherently models a wide range of crops (Not crop A from one source and crop B from another). (eg for UK wheat, barley, potatoes, beet, rape, beans, peas, grass, maize silage).
20. More efforts in crop experiments under changing/changed climate.
21. Better calibration of the model, but in near potential conditions, the model is not too bad, when the characterization of the environment (soil and climate) is well done. In worse conditions, the effects of limiting factors (water, temperature, mineral nutrition) and their interactions need new knowledge. Moreover the risks of evolution of pests and diseases have to be taken into account.
22. Improve crop specific responses to extremely dry and wet conditions (with special attention to timing of the event) particularly heavy precipitation events, especially those leading to excessive soil moisture conditions capable of reducing harvest yields by a combination of impacts on plant function and machinery operations (van der Velde et al., in review).
    Improved understanding of extreme weather impacts on agricultural production, and better representation of associated damage within crop models, which is essential to better quantify future damage and inform adaptation responses.
    Further integration with remotely sensed data, either as input, or as complimentary information so that assessments can use the strengths of both crop models and remote sensing.
    I also support simplifications of the often data-intensive crop models such as EPIC. So - in a way - going back to basics. Depending on the issue one wishes to address (e.g. yield variability under climate change) often simplified and larger scale regional models should be developed and might provide robust responses.
23. Development and testing for extremes, particularly T extremes and interactions like CO_2-T-transpiration.
24. Apart from weather, fertilizer application play an important role. More attention should be given to the role fertilizer/soil fertility in crop modelling.
25. I disagree with the wording of the question. Resources should not be used for new model development. Instead they should be used for crop model improvement, especially as it relates to climate change response and food security issues.
26. We build good crop models, and then use them for different purposes, which may include climate change and food security, but also other topics. We do not build models for climate change research and food security purposes alone. A good model stand securely on its own feet.
27. Generate climate change scenarios over spatial and temporal scales is the biggest problem in this context. if it can be solved it is a valuable work.
28. Current crop models are good enough to predict the effects of changing CO_2 concentration and changing climate; however, to calculate actual yields at the global scale for establishing the current and the future global food production, there are many factors involved (yield losses at harvest, infestation by pests and diseases, weed competition, poor soil quality, etc.) that cannot be modelled but will also not be modelled in the future.
29. Determine more precisely the influence of growing CO_2 and temperature atmospheric variables, including solar radiation, water balances, floods, dryness, on crops plant populations, including weeds and pests.
30. Cooperation between modelling groups
    Modular model format allowing addition and modification of capabilities
    Consistency in data collection.
31. Crop response to increased temperatures during critical development stages - exact figures, instead of vague estimates

Better understanding and forecasting of the impact CC on rainfall variability and intensity, as well as early or late commence or end of cropping/rainy season.

32. Incorporation of effects of extreme weather events, e.g., heat damage and recovery processes; Incorporation of pest and disease impact, especially their occurrence and severity in response to climate change.
33. At larger scale data availability and consistency are the main limitations in my opinion. Furthermore the integration of bio-physical (climate) drivers and socio-economic (policy, market, farmer's behaviour/management would be very relevant. Especially the socio-economic data is difficult to obtain at larger scales in a detailed manner.
34. Multi-physical and chemical processes interaction with multiscale capacity.
35. Should integrate resources to develop a generic process-based crop model that can be incorporated into a larger model easily.
36. At first, it needs some special equipments to collect data regularly and transfer time by time to database center. At second, the precise researcher is needed to follow all of variables and note all events happen during experiment. At third, there should be enough fund to coordinate everything precisely.
37. There is need to involve farmers and policy stakeholders in development and potential uses of model.
38. The most constrain is availability of weather and soil data for a range of locations where one intent to evaluate the effect of climate change on crop performance and provide some insight on adaptation.
39. 1. Crop models should be able to accept data outputs from regional climate models.
    2. CO2 fertilisation should be a standard component of all models
    3. Crop indices in models should not be more closely linked to disparate geographic locations to make results more realistic and reliable.
40. More testing required and integration of different models.
41. Ensure that models respond to changes in temperature, atmospheric CO2, variable rainfall amounts and intensity. Better modelling of runoff, drainage and erosion?
42. Following four developments should be improved and/or developed.
    1. Phenology simulation;
    2. The interaction of co2, temperature, water and nutrient;
    3. The effects of abiotic and biotic stresses;
    4. Integration with social economic and environment impacts models.
43. Much more rigorous testing which is used to guide model revision.
44. They need sufficient scientific basis for development. The models need to understand physiological, agronomic, environmental and other aspects of crp and livestock production for development of algorithms that capture them.
45. There are good models to be use din climate change study and developing adaptation options. However, there are only few individuals who have the know how of models in developing countries where the use of models id most required. Awareness creation and training of young staff in developing countries can bring a wider use of models in these countries.
46. SIMPLIFY THEM
    USER FRIENDLINESS
    STAKEHOLDER INVOLVEMENT.
47. This hard to say give the wide range of crop models.
48. I think that the main lack is the capacity to straightforwardly represent crop-livestock systems (in particular those of smallholders) and the interactions between the different enterprises or products. Less focus on modelling the crop-in-the-field and more focus on considering crops as an important part of the next-higher level of organization is needed to properly explore the options available to landholders.
49. Models that use improved statistical testing. Models flexible to the use of other models.ie. DSSAT only use one water-balance model, proved to be insufficient.
50. Models need to reflect the underlying physics accurately rather than relying on calibration. Calibration generally enforces a stationarity assumption, and climate change scenarios always violate this assumption. Only physically accurate models will be useful for climate change. Another approach is to compare existing ecosystems with other existing systems that closely represent what the existing system will change into in the future.

51. This is a very long survey already. Briefly, I would say that the interaction between processes needs to be better understood. That being said, my experience is that the main problem is misuse of models as users have a hard time catching up obvious mistakes or illogical outputs. While a lot can be done in that regard to help the user through inputs error-catching routines, sometimes it is hard to see users not familiar with broad numbers (e.g. average yields, N yield, erosion rates, harvest index) presenting foul data with full certainty because that was what was printed in the model output. It goes beyond modelling.
52. a) Soil water or precipitation requirements of crops
    b) Critical stages of water/precipitation requirement
    c) Tolerance or resilience of crops in adverse conditions of soil, temps, precipitation and soil fertility
    d) Yield/harvest and its quality
    e) CO_2 analysis e.g. is there CO_2 fertilisation or things getting - tradeoffs.
53. Uncertainty in impact assessments due to the crop model requires better quantification. As has been done for climate modelling this can be done by (i) comparing crop models, and (ii) perturbed parameter simulations for individual crop models.
54. For policy making
    Development of adaptation strategies under varied environmental condition
    Large regional analysis of the effect of weather and management on crop yield
    Vulnerability of crop systems to climate variability.
55. Crop models need to be developed based on the state of the art biological insights. Such a model would need minimum data for parameterization, and have a wider range of applicability than empirical models.
56. Most crop model have been developed to handle a single weather data scenario when studying climate change requires to deal with many of them. Most of them can be used nonetheless by multiplying the simulation runs, but it would be valuable for crop models to handle in a more direct way a climate range (multiple scenario) or optimisation process that would overcome this issue.
57. It is absolutely imperative that we switch from the current "model-as-program" to a declarative modelling approach. Since the 1970s, we have equated the model with the program used to simulate ite behaviour. This has numerous, well-known problems (cost of development, non-transparency, difficult of sharing, etc). The declarative modelling approach is based on the representation of model structure (objects, variables, equations) independently of the code needed to simulate model behaviour. This approach, often based on the use of an XML-based markup language, is now commonplace in other disciplines (electronics, Systems Biology). It means that a wide variety of computer-based tools can be developed for processing the model (display, analysis, code generation for simulation, etc), with any one tool applicable to many models, and any one model processable by many tools. The above comments are generic - they apply to models in many disciplines - but have special relevance to models which address complex interactions between various subsystems, and which directly relate to human issues and needs, since one of the benefits of this approach is to increase the ability of stakeholders to participate in the modelling process.
58. Incentives for people to work together
59. Deliver on multiple outputs - same framework to do potential and actual yield and to do soil C and GHG emissions.
60. Crop models are one of the best available options to integrate changing weather pattern/possibility of a changing weather on plant growth and its yield. The model development has been always been objective driven. With the objective of climate change research, the crop model should be sensitive to the changes in the weather variables and their consequent dynamic processes on plant and soil. Ideally or potentially, the models should be able to incorporate various information arising from many areas of the climate change research from gene to landscape level. Gene level crop models can have an important role in the prediction of the growth of crops which are developed fro drought and pest tolerance. Easily meeting the data requirement of these models is also very challenging and to be taken up. Models have been tested under controlled conditions to changes in CO_2 concentration, their applicability in the filed situation with multiple interaction also need to be considered. Adaptability of micro-organism in soil in the changed environment and its consequence on the nutrient turn over and crop yield also need to be considered.
61. Move to well structure open-source, modular approach.

6. Publications details provided by respondents

The following are references and web site details provided by respondents to the survey per model. Some replication will exist due to multiple responses for the same model.

Model	Publication details
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