COMMENTARY:

Crop–climate models need an overhaul

Reimund P. Rötter, Timothy R. Carter, Jørgen E. Olesen and John R. Porter

Estimates of how much food we can grow in a warmer world are out of date. Researchers need to switch to more rigorous multi-model ensembles.

Adaptation to climate change is a costly business. In the agriculture, forestry and fisheries sectors, it has been estimated by the United Nations Framework Convention on Climate Change that about US$14 billion will be needed annually by 2030 to cope with the adverse impacts of climate change, though this figure could be two or three times greater[1]. Information about the potential impacts of climate change on food supply is badly needed by agricultural policymakers to plan for the coming decades; after all, the United Nations Food and Agriculture Organization estimates that a 70% increase in agricultural productivity will be required by 2050 to meet the growing food demand[2].

Quantification of complex crop–climate–soil interactions is essential for supporting agricultural management strategies and policy decisions at multiple scales, from the farm to the continent. With so much at stake, are our modelling approaches up to the task? No, they are not.

Many of our current models are badly out of date; they do not incorporate the latest knowledge about how crops respond to a changing climate and may not properly represent modern crop varieties and management practices. Furthermore, modellers often fail to quantify the uncertainty of their models — a problem that can promote mistrust in model results and make it difficult for policymakers to act on the information. Impact modellers in general, and crop modellers in particular, need to improve their rigour in the development, testing and application of models. Crop–climate modellers urgently need to embrace methods already prevalent in the climate-modelling community for quantifying the uncertainty in their results. We should focus on multi-model ensemble techniques to assess future crop productivity.

A model approach

Assessments of climate change impacts on global food production and supply rely heavily on process-based modelling. These are the type of models that use our understanding of physical and biological processes (such as how given crops respond to increased carbon dioxide, reduced water supply, warmer growing seasons or changed crop management) to forecast how farm-level productivity may change in the future. Scaled up to larger regions, in combination with projections of future population, trade and commodity prices, this information can help us to estimate the future of the overall system (such as how much food we can grow in a warmer world). Statistical models are less helpful: they are restricted to the climates and atmospheric conditions of today, and commonly fail to take into account interactions between crop genotype and environmental and management factors that are so important for informing adaptation decisions.

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Without complex interactions between many crop, soil, weather and management factors, simple experimental observations would suffice as indicators of future system behaviour. However, the real world is complicated, and integrative tools such as process models can help us to understand and unravel the complexities.

Since the late 1980s, such models have helped to assess the potential impacts of anthropogenic climate change on crop productivity. The emphasis of these studies was originally to understand the likely risks posed to future productivity, but more recently the focus has shifted towards informing adaptation strategies for managing these risks.

These are admirable goals, but the majority of models that are applied to this problem were developed at least two decades ago. Though they have been re-calibrated over time, they urgently need to be updated to reflect new research in crop physiology, agronomy and soil science.

For example, field experiments within the past decade or so have shown that when temperatures go above thresholds of about 30–36 °C during flowering, crops including wheat, rice and maize experience a sharp decline in grain set and yield[3,4]. Most process-based models do not account for this, and so tend to overestimate future yields in regions experiencing more frequent hot days during the growing season[3].

Similarly, it is known that increased carbon dioxide concentrations can limit the loss of water through the stomata of plant leaves — the pores through which plants transpire[5]. However, many models lack explicit details about photosynthesis and can't account for the interaction between water use and production. As such, they may overemphasize the effects of future droughts.

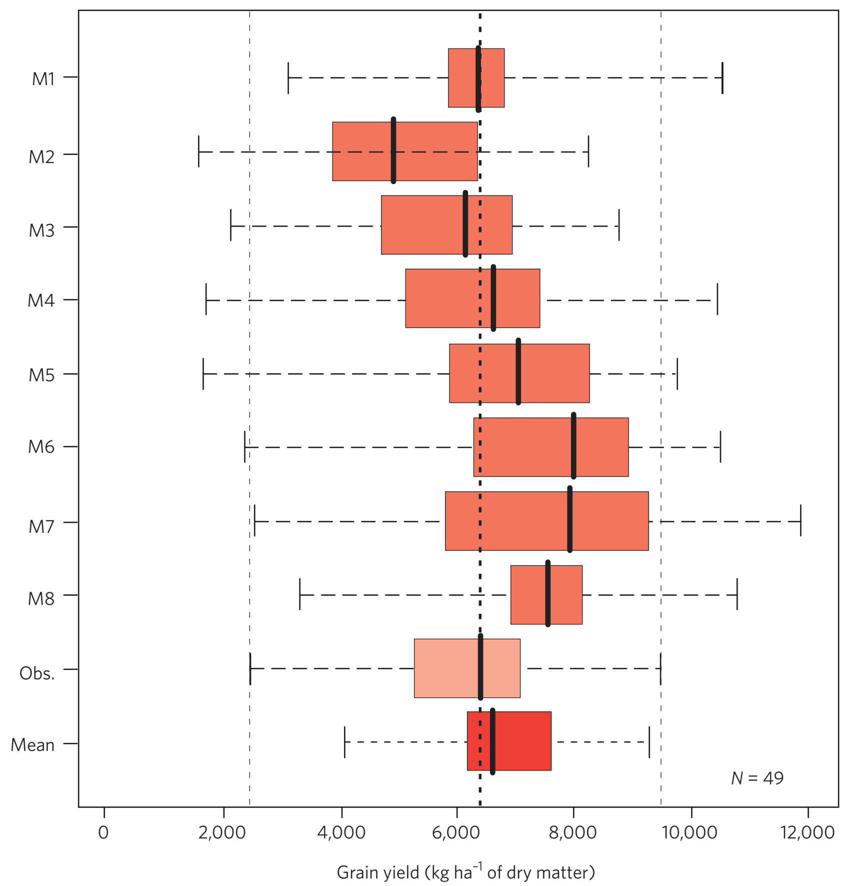

Figure 1 | Simulated grain yields for winter wheat vary greatly between eight different models (M1–M8); the multi-model mean is quite close to the observed (Obs.) results. *N* is the sample size of grain yields; the whiskers show minimum and maximum values; three vertical dashed lines indicate observed minimum, median and maximum values as a reference. Figure reproduced with permission from ref. 8, © 2011 Elsevier.

Strength in numbers

Thanks to the complexity of crop systems, many models do not agree on what the future will bring. One analysis, for example, compared five different models of winter-sown wheat in New Zealand with observations from1991–92; yields were off by up to 20%, and the models differed even more in estimating other variables such as final above-ground biomass[6]. Other studies on wheat and potato have shown similarly variable results from different models. In 2002, the authors of one such study[7] concluded that further work was needed to pin down the reasons for these large inter-model differences.

Progress has been slow. New results from model intercomparisons for winter wheat in Europe (Fig. 1) still show considerable differences in estimates of grain yield between models, and between the models and field observations[8]. Some of these differences might disappear when models are updated with recently acquired knowledge. But some differences will surely remain. We will need targeted experimentation to gain insight into agricultural processes that are as yet poorly understood.

Only recently has the urgent need for such intercomparison studies been re-iterated[9] and acted on internationally, through such efforts as the Agricultural Model Intercomparison and Improvement Project (www.agmip.org). This project, launched in October 2010, aims to build a transdisciplinary modelling framework to provide more robust estimates of climate impacts on crop yields and agricultural trade, including estimates of associated uncertainties. We expect that this effort, of which we are participants, will set new global standards for modelling crop yields.

Multi-model ensemble simulations provide a valuable way of estimating the range of possible outcomes, and of unpicking the importance of different physical and biological processes written into the models. This is an important lesson already learnt by climate researchers, who have been able to exploit advances in computing power to explore uncertainties in their projections. Crop simulation offers a substantially lower computational challenge than climate modelling, so there should be no real obstacle to the use of ensemble approaches in crop impact assessment. As there is clearly no best model, determining multi-model averages is a promising practice that can help to better replicate observed results (Fig. 1). Although this result would seem to offer attractive predictive potential, caution is needed. Similarity to observations may simply reflect a fortuitous cancelling of errors among models, a situation that cannot be relied on under future conditions where key responses absent from some models may become dominant[10].

Better by design

To improve the situation, we need to go back to basics. Our work should begin in the classroom: there is an acute need for intergenerational transfer of existing knowledge in crop physiology and agronomy as well as training in the development and application of models.

In terms of research, we should start by reviewing existing models to see where the big deficiencies are in understanding crop growth and development processes. Obvious gaps at present include plant responses to increased carbon dioxide concentrations over a wide range of crops and environments, and the responses of leaf area and grain setting to stress factors. Second, there needs to be a bigger effort to generate and compile high-quality field data, at the scale of whole farms, for model testing. One perfectly achievable goal would be to develop high-quality data sets at about ten sites worldwide for each crop type. Third, we need to develop better methods to estimate larger-scale regional productivity. Models are built to deal with plant processes studied at the scale of single plots; we need to find ways of getting those models to account for the variable landscape and environmental conditions across larger areas. Fourth, even with improved models, intercomparison will remain a vital tool in testing model performance and sensitivity to different environments. Researchers should be doing more of this.

Finally, crop–climate modellers must be careful to report their level of certainty. This is the most immediate and important research requirement, especially when results are being used to inform decisions. Given the numerous sources of uncertainty in the field, it is remarkable that confidence intervals are often absent from published studies. The community needs to develop formal protocols for reporting uncertainties in crop-model predictions, analogous to those used for climate[10]. We encourage the Agricultural Model Intercomparison and Improvement Project to coordinate such efforts and develop appropriate recommendations. The habitual use of multi-model ensembles would help to facilitate this development.

There is an urgent need for more quality, transparency and consistency in the modelling methods used for assessing climate change impacts on crop production. The approach argued for here would provide a firm basis for delivering more robust and usable information, for everyone from farmers to policymakers. ❐

Reimund P. Rötter[1], Timothy R. Carter[2], Jørgen E. Olesen[3] and John R. Porter[4] are at [1]MTT Agrifood Research Finland, Lönnrotinkatu 5, FI-50100 Mikkeli, Finland, [2]Finnish Environment Institute (SYKE), Box 140, FI-00251 Helsinki, Finland, [3]Aarhus University, Blichers Allé 20, Box 50, DK-8830 Tjele, Denmark, [4]University of Copenhagen, Hoejbakkegaard Alle 9, DK-2630 Taastrup, Denmark.*
**e-mail: reimund.rotter@mtt.fi*

References
1. Frankhauser, S. *et al. WIREs Clim. Change* **1,** 23–30 (2010).
2. Petherick, A. *Nature Clim. Change* **1,** 20–21 (2011).
3. Porter, J. R. & Gawith, M. *Eur. J. Agron.* **10,** 23–36 (1999).
4. Rötter, R. & van de Geijn, S. *Climatic Change* **43,** 651–681(1999).
5. Ewert, F. *et al. Agr. Ecosyst. Environ.* **93,** 249–266 (2002).
6. Jamieson P. D. *et al. Field Crop. Res.* **55,** 23–44 (1998).
7. Tubiello, F. N. & Ewert, F. *Eur. J. Agron.* **18,** 57–74 (2002).
8. Palosuo, T. *et al. Eur. J. Agron.* (in the press).
9. Rosenzweig, C. & Wilbanks, T. J. *Climatic Change* **100,** 103–106 (2010).
10. Knutti, R. *et al.* in *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Assessing and Combining Multi Model Climate Projections* (eds Stocker, T. F. *et al.*) 1–13 (IPCC Working Group I Technical Support Unit, 2010).

Published online: 19 June 2011

COMMENTARY:
Meet the humanities

Mike Hulme

An introduction needs to be made between the rich cultural knowledge of social studies and the natural sciences.

The Editorial in the first issue of *Nature Climate Change* remarked that “climate change is now as much a societal problem as a physical one”[1]. Although climate is inarguably changing society, social practices are also impacting on the climate. Nature and culture are deeply entangled, and researchers must examine how each is shaping the other. But they are largely failing to do so.

A recent study[2] analysed the disciplinary source literatures of the three working groups for the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). It showed that the cited literature was heavily dominated by natural science disciplines, especially the Earth sciences, while the minority social science content was heavily dominated by economics. Literature from the humanities was virtually absent. The view of climate change thus constructed by the IPCC — and the view that therefore has circulated through societies and influenced policy — is heavily one-sided. Although there may have been some modest broadening of disciplines sourced in the IPCC’s fourth assessment report and the forthcoming fifth assessment report, the analysis of anthropogenic climate change continues to be dominated by positivist disciplines at the expense of interpretative ones[3,4].

This partiality matters profoundly, because such assessments determine the framing of what exactly is the climate change ‘problem’ that needs to be ‘solved’, and they set the tone for the human imaginative engagement with climate change. Over its 23-year history, the IPCC has been presented as the authoritative voice of climate science and the global knowledge community. How the idea of climate change is framed by the IPCC therefore carries enormous significance for the subsequent direction, tone and outcome of policy and public debates. As