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Adapting crops and cropping systems to future climates to ensure food security: The role of crop modelling

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ABSTRACT

Food production systems in the next decades need to adapt, not only to increase production to meet the demand of a higher population and changes in diets using less land, water and nutrients, but also to reduce their carbon footprint and to warmer temperatures and altered precipitation patterns resulting from climate change. Crop simulation models offer a research tool for evaluating trade-offs of these potential adaptations and can form the basis of decision-support systems for farmers, and tools for education and training. We suggest that there are four areas in adapting crops and cropping systems that crop modelling can contribute: determining where and how well crops of the future will grow; contributing to crop improvement programmes; identifying what future crop management practices will be appropriate and assessing risk to crop production in the face of greater climate variability.

1. Introduction

With the global population predicted to increase to around nine billion people by 2050, and with changing diets due to rising incomes, a recent analysis relating calorie and protein consumption to GDP estimates that food production needs to increase by 100–110% by 2050 (Tilman et al., 2011). This, together with the need to conserve other land uses, such as forests and wetlands, for other essential ecosystem services such as carbon storage and biodiversity, poses a real challenge, particularly as it needs to be set against a backdrop of climate change, which, despite efforts to mitigate by reducing anthropogenic greenhouse gas (GHG) emissions, will still occur to a degree that will mean higher CO_2 levels, warmer temperatures and changed precipitation patterns in many regions.

Clearly, our current crop production systems will need to adapt to meet these changing pressures. Adaptation may be either planned or autonomous (Easterling et al., 2007, p. 294). Planned adaptation is more at the governmental level, and involves changing the decision-making environment through developing infrastructure (e.g. irrigation, markets), providing relevant information to farmers (e.g. suitable crops and optimum times to grow), and developing technical improvements through publicly-funded research (e.g. biotechnology advances). Autonomous adaptation, on the other hand, is more at an individual farmer level, and involves changes in agricultural practices that may occur by trial-and-error, farmer experience, or by changes in the decision-making environment resulting from planned adaptation. Within this context, we see four broad areas of adaptation of crop production systems as climates change: (a) new crops being introduced and previous crops being phased out; (b) development of new varieties of existing crops; (c) evolution of crop management practices and (d) dealing with climate uncertainty through the provision of information.

These adaptations will involve many trade-offs, and possibly some synergies, at different scales, requiring decisions to be made. Closing yield gaps, for example, is likely to require increased irrigation, but this may take water from other uses. Reducing application of nitrogenous fertilisers to decrease nitrous oxide emissions has obvious implications for crop yields. The need to understand these interactions has led to a renewed interest in the use of crop models as key tools to contribute to research, decision-support and knowledge exchange on climate change and food security across a wider range of disciplines and spatial and temporal scales (see, for example, the Agriculture Modelling Intercomparison and Improvement Project, AgMIP, www.agmip.org). In this paper, we discuss how crop modelling could contribute to the four broad areas of adaptation in crop production systems identified above, and how it might be used to analyse some of the trade-offs involved.

2. Current and future crop geospatial distribution

Future climates are likely to shift the regions of optimum productivity of crops, with both winners and losers. Africa,

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for example, is predicted to become warmer and drier, and although there is huge uncertainty and local variation, agriculture there is likely to be negatively affected as a result (e.g. Müller et al., 2011). Even in temperate climates, if existing crop varieties continue to be used, there could potentially be a decline in yields due to faster crop maturation, less water availability, more erratic weather, or the incursion of new pests and diseases. However, shifting climates may also bring new opportunities such as a northern migration of suitable crops, even to regions that currently do not support agriculture. In other cases, farmers may be able to adapt by diversifying their income from a greater range of crops or use of currently under-utilised crops (e.g. dual-purpose sweet potato, Claessens et al., 2012).

One approach to gain some insight into which crops might grow where in the future is to identify 'analogue climates' in existence now which have similar climate parameters to future climates (e.g. Burke et al., 2009). Varieties, crops and management practices in these analogue climates may give some indication of what may be possible in the future for a particular location. While it is not claimed that analogue climates will match future climates exactly, this information can at least provide the basis for discussion and further analysis as to whether such possibilities are likely under given local social, economic, cultural and political conditions. It should also provide guidelines as to what adaptations might need to be made to existing crop production practices, the influence of social attitudes, and what infrastructure (e.g. markets, transport, processing plants, etc.) might need to be put in place to capitalise on new opportunities. This could be followed by further detailed crop modelling studies to refine these necessarily broad indications, taking into account, for example, land capability and pest and disease risks, although there may be a need to improve current crop models to achieve this (Rötter et al., 2011).

Various constraints will limit the migration of crop production with climate change, including geographical barriers imposed by terrain. Bachelet and Kropff (1995), for example, estimated the changes in rice crop extent in south-east Asia, but made the point that its move northwards was limited by the presence of the Himalayan mountain range. Similarly, other land uses, such as forests and wetlands, currently providing essential ecosystem services, will also constrain the amount of land that can be used for arable agriculture, although in some cases, trade-offs between food production and these other ecosystem services may have to be made (West et al., 2010). It is possible that current marginal land might be pressed into production, in which case crop modelling can be used to evaluate likely crop productivity there, but for the very reasons that it is currently marginal, it is unlikely that it will contribute significantly to a doubling of food production. Indeed, most of the doubling in food production since the Green Revolution in the 1960s has come from increases in yield per area, and only small increases in cropped area (11% increase from 1961 to 2007, Foley et al., 2011). It is likely that the doubling in food production required for the future will continue to follow this trend.

Estimates for the importance of pests and diseases for yield loss are typically around 50%, but can be up to 82% (Oerke, 2006). Pests and diseases will move with shifts in crop distribution to some extent, or there will be new combinations as the two move at different rates. A good example of this was demonstrated for winter oilseed rape where a crop yield simulation model, when combined with a weather-based epidemiological model, showed that under 2020 and 2050 climate change scenarios yields of susceptible varieties could decrease by 50% in England but could increase by 15% in Scotland because of the differential abilities of the disease to cope with the fungicides applied (Butterworth et al., 2010).

With increasing areas of fertile arable land being lost to urbanisation, one area that deserves more attention from crop modellers is that of urban agriculture, on dedicated areas within city boundaries and even on rooftops. Although figures are scarce, around 15–20% of world food production may be produced within cities (Armar-Klemesu, 2000), a figure that is only likely to further increase in the future (de Zeeuw et al., 2011). There has been a technological surge in production practices of high value crops such as vegetables in urban environments, but the limits to water recycling, optimisation of growing substrates, climatic controls and impact, and variety selection needs robust crop modelling linked to water supply and quality modelling, spatial planning and architectural suitability to understand and optimise the influence of urban microclimates on crop growth, and identify best practices and trade-offs compared to rural agriculture.

3. Contribution to crop improvement programmes

Many of the studies that investigate the opportunities for adaptation to climate change and sustainable intensification emphasise the role of genomics research in modifying plant function, through, for example, increasing rates of photosynthesis by transferring C4 pathways into C3 species, introducing nitrogen fixation into cereals, increasing resistance to pests, diseases, drought, heat and salinity, and utilising hybrid vigour (Royal Society, 2009). With many of these modifications, there are trade-offs to be made: increasing photosynthetic rates, for example, may mean that protein contents are lower, while N fixation in cereals and resistance to pests and diseases may have implications for the plant's energy budget (Foresight, 2011). Breeding for drought resistance by selecting for deeper rooting characteristics may divert biomass away from the shoots and yield component, resulting in less yield in good years. Even breeding crops with improved nitrogen uptake ability will be limited by the amount of N available in the soil, and increasing nitrogen use efficiency implies lower protein content, adversely affecting nutritive value. In many cases, adaptations at the genotype or plant level do not scale to farm or landscape level improvements due to many other influences operating, such as resource availability, soil constraints to root growth, pests, weeds and diseases, and socio-economic factors. Crop models with the appropriate level of detail, perhaps together with other types of model, should be able to help to tease out some of these interactions.

The use of crop models in crop improvement programmes has already begun, but their potential in helping to identify and evaluate desirable plant characteristics, environmental characterisation, and explaining genotype-by-environment interactions needs to be explored further. Recent advances in biotechnology are also opening up new opportunities for crop improvement through such techniques as molecular marker assisted selection and genetic engineering for a wide range of crop species, and there is, therefore, likely to be a crucial role for crop simulation models to play in linking information at the genotype level to that at the phenotype. However, it is not clear as yet how this should be done, the big gaps in our knowledge are the mechanisms whereby proteins are formed from their constituent amino acids. In the long-term, the emerging field of proteomics may provide answers in this direction, although the indications so far are that enormous computing power is required to simulate the processes of folding during protein formation. Initial progress can be made by linking allelic effects directly to phenotypic responses, and using this as input for models of plant breeding systems (Chenu et al., 2009). More precise definition of the actual genetic architecture of various phenotypes would be a logical next step. Attempts to use crop simulation models to link quantitative trait