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Crop modelling for integrated assessment of risk to food production from climate change☆

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ABSTRACT

The complexity of risks posed by climate change and possible adaptations for crop production has called for integrated assessment and modelling (IAM) approaches linking biophysical and economic models. This paper attempts to provide an overview of the present state of crop modelling to assess climate change risks to food production and to which extent crop models comply with IAM demands. Considerable progress has been made in modelling effects of climate variables, where crop models best satisfy IAM demands. Demands are partly satisfied for simulating commonly required assessment variables. However, progress on the number of simulated crops, uncertainty propagation related to model parameters and structure, adaptations and scaling are less advanced and lagging behind IAM demands. The limitations are considered substantial and apply to a different extent to all crop models. Overcoming these limitations will require joint efforts, and consideration of novel modelling approaches.

1. Introduction

The use of dynamic, process-based crop and cropping system simulation models for climate change impact and risk assessment studies has become increasingly important (Tubiello and Ewert, 2002; Challinor et al., 2009a; White et al., 2011; Rötter et al., 2012a; Angulo et al., 2013b). Initiated by the pioneering work of

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de Wit (1965) and Monteith (1965a), crop model development spans a period of nearly five decades (Donatelli et al., 2002; van Ittersum et al., 2003; Boote et al., 2013). Presently, a range of models at differing degrees of model complexity and emphasis on different research questions, crops and regions has become available (Challinor et al., 2009a; Soussana et al., 2010; White et al., 2011; Asseng et al., 2013).

Most early crop models were not primarily developed for large-area climate change impact studies, but for application at the plot or field scale, with single crops and a limited range of management options over one or a few seasons. They were developed to integrate and document current understanding of crop physiology and its ability to quantify the effects of environment and basic management on crop productivity. More recently, emphasis has been placed on improving model flexibility to support the simulation of different crops, cropping systems and production situations (Donatelli et al., 2002; Keating et al., 2003; Adam et al., 2012a, 2012b; Brown et al., in this issue). Early applications of crop models in climate change impact studies were mainly site-based, referring to individual fields, to estimate the impacts of possible climate change on selected crops (Bindi et al., 1996; Semenov et al., 1996). Later efforts tried to assess climate change impacts for larger areas such as regions, nations, large watersheds and/or globally (Rosenzweig and Parry, 1994; Rötter et al., 1995; Easterling et al., 2007). Recently, crop modelling studies for climate impact research have become more elaborated (Eckersten et al., 2001; Tao et al., 2009b; Iizumi et al., 2011; Rötter et al., 2012a; Elliott et al., 2013; Hawkins et al., 2013b; Rosenzweig and Neofotis, 2013; Tao and Zhang, 2013a) and crop models for large area application were developed (Challinor et al., 2004; Bondeau et al., 2007; Tao et al., 2009a). To better understand the risks of climate change for crop and food production explicit attention has been given to issues of model uncertainty with specific emphasis on multi-model ensemble simulations (Palosuo et al., 2011; Rötter et al., 2012b; Asseng et al., 2013), up-scaling (Ewert et al., 2011), adaptations (Howden et al., 2007; Moriondo et al., 2010a; Lobell et al., 2011b) and the impact of extreme events (Challinor et al., 2005; Asseng et al., 2011; Moriondo et al., 2011; Eitzinger et al., 2013; Lobell et al., 2013; Tao and Zhang, 2013a; Teixeira et al., 2013).

The complexity of climate change impacts and adaptations for managing climate risks and improving food security calls for more integrated modelling and quantitative assessment approaches that go beyond the sole biophysical aspects of crop and cropping systems as recently stressed by Wheeler and von Braun (2013) and the IPCC 2014 Working Group II report (Porter et al., 2014). During the 1990s, a few examples of integrated regional assessment modelling were reported in which crop model output was utilized systematically in assessing agricultural land use potential and constraints, and for optimizing land and resource use to meet multiple regional development goals (van Ittersum et al., 2004; Rötter et al., 2005), though not yet in the context of climate change. Later, integrated assessment modelling (IAM), see definitions in Jakeman and Letcher (2003) and Laniak et al. (2013), increasingly received attention in climate impact research (e.g. Lehtonen et al., 2010; Nelson et al., 2013) with crop models forming an integral part of the modelling chain (Bland, 1999; Harris, 2002; van Ittersum et al., 2008; Ewert et al., 2009; Bergez et al., in this issue). As part of this model integration, a number of issues (e.g. scale of application, integration of sub-models, uncertainty propagation) have become apparent that must be addressed to achieve a sound conceptual, methodological and technical integration of crop models within IAM for climate change risk assessment. Yet, the information on such limitations is fragmented and solid conclusions for crop modelling have not been drawn. This points to the need for a comprehensive overview of recent advances in crop modelling contrasted with the requirements on crop models for use in IAM of risks to food production from climate change.

Accordingly, the present study aims to (i) review the state of the art in crop modelling and (ii) characterize the demand of IAM on crop modelling for assessments of climate change risks to food production in the context of food security. The main focus is on food cropping systems, though it is expected that many issues explored here will also apply to arable systems for feed, fibre and bio-energy production and grasslands.

First, the context of climatic change risk for crops and cropping systems is reviewed. Following this, a framework for conceptualizing integrated assessment modelling for climate change risk to food production is provided with a description of the current state of the art of crop models, as relevant for climate impact assessments. The final section summarizes the key requirements of IAM for crop models and their current state of development to meet these demands. Finally, key challenges and priorities for crop model improvement and development to better serve climate change risk assessment are identified and conclusions for future research are drawn.

2. Risks to food production from climate change

2.1. Framing climate risks

Historical weather records show that global warming is causing changes in temperature and rainfall patterns and has increased the frequency and severity of extreme events (Lamb, 1995; Trenberth, 2011; Coumou and Rahmstorf, 2012; Field et al., 2012; Liu and Allan, 2013). Such changes are also projected by climate models for future conditions (Meehl et al., 2007a; Solomon et al., 2007; Rummukainen, 2012; Sloth Madsen et al., 2012; Taylor et al., 2012). How climate change and extreme weather events translate into agricultural risk depends on the magnitude, likelihood (frequency), and certainty of the impacts, as well as the system's vulnerability (i.e. ability to cope with its consequences) (e.g. Parry, 2007). As such, large impacts associated with increased climate variability (Lobell et al., 2011a; Gourdji et al., 2013; Lobell et al., 2013) and increases in mean temperatures for crops now grown at or near their thermal optimal (Porter and Semenov 2005, Hatfield et al., 2011; Sánchez et al., 2014) pose an immediate source of risk to food production. Risk will, however, vary between crops and regions and with people's socio-economic conditions (Kates et al., 2012; Dow et al., 2013). The high degree of uncertainty in knowing what the mean and variation in climate variables will be in the future (Rummukainen, 2012; Sloth Madsen et al., 2012; Rummukainen, 2014) and what the resulting impacts on crops in combination with elevated CO_2 concentrations will be (Asseng et al., 2013; Rötter et al., 2013) poses considerable challenges for planning and investments in development (Trnka et al., 2014).

2.2. Observed climate changes and impacts on crops

While the past centuries have experienced relatively warm and cool periods, as well as periods with more variable and extreme weather than at present (Lamb, 1995; Büntgen et al., 2011), the recent rate of global warming is unprecedented. Globally, there is unequivocal evidence that recent decades have experienced record high temperatures (e.g. IPCC, 2007; Stocker et al., 2013) and mounting evidence that extreme events are occurring more frequently than they did during most of the 20th century (Alexander et al., 2006; Trenberth, 2011; Field et al., 2012; Handmer et al., 2012; Hansen et al., 2012; Seneviratne et al., 2012). These changes have had distinct implications for agricultural