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Editorial

Modeling crops from genotype to phenotype in a changing climate

Climate change is exerting daunting challenges to world agriculture. Several studies have shown that modern crop cultivars are not well adapted to the recent climate changes (Brisson et al., 2010; Oury et al., 2012). Crop models are potentially able to capture crop genotype-to-phenotype relationships. They are hence a helpful tool to identify and assess the effectiveness of improved crop traits and to support the efficiency of plant breeding programs (Messina et al., 2009; Martre et al., 2014; Hammer et al., 2016). A recent compilation of studies (Yin and Struik, 2016) described some of the progress in combining crop modelling and genetics but it also recognized that current crop models need upgrading. This special issue aims to contribute to the further development of this research area with a particular focus on crops grown under a changing climate. It presents results of a workshop of the Wheat team (https://www.agmip.org/s/wheat/) of The Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig et al., 2013) and of the Expert Working Group on Wheat Plant and Crop Modeling of the Wheat Initiative (http://www.wheatinitiative.org/activities/expert-working-groups/wheat-plant-and-crop-modelling) in 2014 at INRA Clermont-Ferrand, France, and includes also invited papers. The contributions cover three main areas.

1. Improving crop growth models to account for climate change impacts

Several recent papers (e.g. Rötter et al., 2011; Boote et al., 2013; Ewert et al., 2015), have discussed the need for an upgrading of current crop models to efficiently project the growth of crops under conditions that will more often be encountered in future climates, with higher temperature, more frequent heat spells, more severe and longer periods of drought, or flooding. To improve crop models, an important step are model inter-comparison studies, which requires a level of international coordination that has only recently been made possible by AgMIP, and in Europe by the project on Modelling European Agriculture with Climate Change for Food Security of the Joint Research Programming Initiative on Agriculture, Food Security and Climate Change (http://macsur.eu/).

Two papers in this special issue report results from such concerted research actions. Maiorano et al. (2017) present the first concerted crop model improvement study following up on recent wheat model intercomparison exercises (Asseng et al., 2013; Asseng et al., 2015; Martre et al., 2015; Cammarano et al., 2016), where 15 models were improved for predicting the impact of high temperature on wheat crop growth and yield. The authors show that the improvement of individual model skills translates into a reduced uncertainty of the multi-model ensemble prediction and in a reduction by half of the number of models which are needed in a multi-model ensemble to stay within acceptable uncertainty range.

Heat stress signals are in the form of absolute temperature thresholds above which the formation of reproductive sink (Alghabari et al., 2014; Prasad and Djanaguiraman, 2014) or leaf senescence (Zhao et al., 2007) could be adversely affected. Under warm conditions the air and surface temperatures can differ by more than 10 °C (Siebert et al., 2014) and heat stress effect on sink formation or leaf senescence are likely determined by tissue or canopy temperature (Eyshi Rezaei et al., 2015). It may thus be more important to consider the organ or canopy temperature as the driving variable of crops to heat stress rather than air temperature as typically used by most crop models so far. But how good are current crop models to predict canopy temperature? What is the importance of considering canopy temperature to simulate the impact of heat stress on grain yield formation? These questions were addressed by Webber et al. (2017), who evaluated nine wheat crop models that implement different mechanistic or empirical algorithms to calculate canopy temperature. The models varied widely in their ability to simulate measured canopy temperature and in general had better predictions of yield when calculated canopy temperature was used to model the effect of heat stress on processes determining grain yield but the improvement was relatively small.

Several studies have previously suggested that the level of sink limitation of yield formation may significantly increase under future climate. Shi et al. (2017) studied the effect of high night temperature on rice yield formation under different levels of nitrogen supply. They used a novel modeling approach to quantify source–sink relationships during the grain filling period and showed that increased nitrogen application does not alleviate the impact of high night temperature on source-sink interactions across cultivars and seasons (water supply). However, genetic differences in the tolerance to high night temperature appeared to be related to genetic differences in sink size. Transparent evaluation of crop models with detailed field studies is an important aspect of model improvement that helps to set the limits of the conditions under which a given model can be used with enough confidence and to identify aspects where improvements are needed. Asseng et al. (2017) used field experiments with modified sink–source relationships to explore how the Nwheat crop model respond to such modifications. The authors show that their model is able to reproduce several experimental treatments with reduced source (e.g. crop shading) or sink (e.g. ear halving) but they also identify deficiencies in simulating grain set and final grain size, point to areas

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where Nwheat, and most likely other wheat and cereal models, need improvement.

2. Modeling the response of genotypes to the environment

More than two decades ago researchers have started to emphasize the potential role that crop models could play for crop improvement (Shorter et al., 1991). Since then important milestones have been reached with the use of crop models to characterize breeding and production environments (e.g. Chenu et al., 2013; Harrison et al., 2014), the development of QTL-based models (e.g. Quilot et al., 2005; Yin et al., 2005; Zheng et al., 2013), and more recently the link of crop models with genomic prediction models (e.g. Heslot et al., 2014; Technow et al., 2015). Several articles in this special issue contribute to the advancement of genotype to phenotype modelling.

Most underrepresented so far are studies that aim to link crop system models with understandings of gene action at the molecular level. In this special issue Chew et al. (2017) present such an effort in the model species *Arabidopsis thaliana* and discuss avenues to further extend on cross-disciplinary work for crop species. The type of models presented by Chew and coworkers represent a new step in integrating knowledge across biological scales with significant potential to contribute to crop improvement. Uptmoor et al. (2017) combined a genome-wide prediction model with a process-based flowering time model to predict the heading time of the progeny of a barley population in independent environments.

Rice, like several other cereal species, shows large adaptive phenotypic plasticity enabling yield stability across environments. Such plasticity is often observed between tiller production and panicle size. In their paper Kumar et al. (2017) report on the plasticity of organ size and number of 12 high-yielding rice genotypes of high and low tillering plant types. They show that most of the observed genetic variations in morphological and yield component traits can be predicted by the rice model SAMARA and discuss the possibility offered by such a type of process-based models to predict the response of new ideotypes to changing environments and crop management practices.

Gouache et al. (2017) used a modified version of the phenology module of the wheat model ARCWHEAT parametrized for hundreds of genotypes to analyze the possibilities to adapt wheat to future growing conditions in France. Their results suggest that the beginning of stem extension can be advanced by several weeks without significant risk of frost damage and that photoperiod insensitive PpdD1 and spring type Vrn3 allele combinations are undesirable. The authors discuss the need, in addition to crop modeling, to use available knowledge in crop physiology and of the allelic variability at the loci underpinning important traits in gene pools to implement breeding ideotypes in commercial improvement programs.

Global simulation studies usually do not consider the adaptation of cultivars to regional or sub-regional climate, soil properties, and crop management practices, which limits our capacity to analyze the impacts of growing conditions on food security. Gbegbelegbe et al. (2017) calibrated the wheat crop model CROPSIM-CERES for modern high-yielding cultivars adapted to the 17 CIMMYT wheat mega environments. Their results show that the use of *ex-ante* calibrated region-specific cultivars improves significantly the model skills for predicting grain yield at country level. This study is an important step to reduce the uncertainty of the projections of regional and global wheat production to enable advanced studies on food security to address questions related to the impact of genetic improvement and agricultural technology with climate change.

Comprehensive model testing is often a neglected aspect to identify model strengths and deficiencies. Raymundo et al. (2017) present a comprehensive field testing of the SUBSTOR-potato model with experiments carried out in 19 countries. They show that while tuber yield is in general well simulated, for different potato species and cultivars, the response of the model to elevated atmospheric CO_2 concentration and high temperature needs to be improved before it can be used to project the impact of climate change and discussed how its skills can be enhanced.

3. Modelling the impact of climate change on grains and seeds quality

Studies of the impact of climate change on food security issues have essentially focused on crop production, while nutritional and functional quality aspects of grains have received limited attention (Müller et al., 2014). This is at least partly due to the limited capability of most crop models which are typically restricted to predicting average grain size and protein or oil concentration (Martre et al., 2011). In this special issue Nuttall et al. (2017) review the current knowledge of the response on wheat grain functional properties to high temperature and elevated atmospheric CO_2 concentration. The authors also discuss how the capability of wheat crop models to consider quality aspects can be advanced and provide a conceptual framework to model the size distribution of gluten proteins and grain distribution using a single spike approach.

The rise in global temperature is also a concern for sunflower quality. High oleic sunflower hybrids are increasingly grown worldwide as their higher content in unsaturated fatty acids compared with traditional hybrids increases the storage life of oil and because of the potent hypocholesterolemic effect of unsaturated fatty acids. However, the percentage of oleic acids in the oil decreases under warmer night temperatures (Aguirrezábal et al., 2014). Here, Angeloni et al. (2017) explored the response of sunflower phenology and seed oleic acid percentage to temperature for high oleic hybrids of sunflower grown in a network of field experiments in the argentine sunflower growing regions. The authors used these information to calibrate a sunflower model and to project the impact of a future global warming scenario on oil oleic percentage at different sites with different sowing dates. Their results provide important information to optimize the conditions to phenotype for high oleic percentage in both controlled and conditions field, and identifies traits on which breeders should focus to improve oil quality in the future.

In summary, this special issue presents promising advances in modeling the improvement of crop species under climate change and future growing conditions. They represent significant efforts to reduce model uncertainty to improve confidence in using crop models in climate change impact studies to support the breeding of genotypes better adapted to future growing conditions. Much more research will be required and we hope that the publication of this special issue will catalyze more activities in this emerging research area.

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