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Baseline simulation for global wheat production with CIMMYT mega-environment specific cultivars☆

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ABSTRACT

Climate change is expected to impact global food supply and food security by affecting growing conditions for agricultural production. Process-based dynamic growth models are important tools to estimate crop yields based on minimum inputs of climate, soil, crop management, and crop cultivar parameters. Using region-specific cultivar parameters is critical when applying crop models at a global scale because cultivars vary in response to climate conditions, soils, and crop management. In this study, parameters were developed for modern cultivars representing all 17 CIMMYT wheat Mega Environments (MEs) using field experimental data and genetic cultivar relationships for the CROPSIM-CERES model in DSSAT v 4.5 (Decision-Support System for Agrotechnology Transfer). Cultivar performance was tested with independent CIMMYT breeding trial field experiments across several locations. Then crop simulations were carried out at $0.5 \times 0.5^\circ$ pixels for global wheat-growing areas, using cultivars representing MEs, soil information, region-specific crop management, and initial soil conditions. Aggregated simulated wheat yields and production were compared to reported country yields and production from Food and Agriculture Organization (FAO) statistics, resulting in a Root Mean Square Error (RMSE) of 1.3 t/ha for yield and 2.2 M t/country for country production. Some of the simulated errors are relatively large at country level because of uncertainties in pixel information for climate, soil, and crop management input and partly because of crop model uncertainties. In addition, FAO yield statistics have uncertainties because of incomplete farm reports or poor estimates. Nevertheless, this new cultivar-specific, partially-validated global baseline simulation enables new studies on issues of food security, agricultural technology, and breeding advancement impacts combined with climate change at a global scale.

1. Introduction

Climate change is expected to impact global food security by altering crop growing conditions and increasing demand for agricultural production (Brown and Funk, 2008; Nelson et al., 2010; Schmidhuber and Tubiello, 2007; Vermeulen et al., 2012). Local and region-specific conditions, changes, and interactions between cultivars and soils must be considered to understand the global impacts of climate change on agricultural production. Field experiments alone cannot predict and quantify the influence of climate change on crop production across the wide range of possible growing conditions (Parry et al., 1999). However, process-based dynamic crop growth models can simulate daily crop growth and development rates throughout a growing season for a wide range of

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growing conditions as well as current and future scenarios (Jones et al., 2003). The strength of such models is their ability to integrate the effects of temporal and multiple stresses on crop growth under different environmental and management conditions (Basso et al., 2011a). After crop models are evaluated over a wide range of environments (Adam et al., 2011), they can be used to transfer findings from experiments across a wide range of environments (Parry et al., 1999). However, crop models are point-based and require point- (or location-) specific input information. For regional and global studies, point-based simulations can be up-scaled by adding each simulated pixel (Ewert et al., 2011; Van Bussel et al., 2011). Also, some crop simulation models have been simplified to simulate yields directly at regional scales (Bondeau et al., 2007; Challinor et al., 2004).

Most crop models require daily climate data, soil characteristics, management, and crop genetic information. At specific locations, soil sampling or farmers' knowledge can be used to obtain soil information (e.g., initial soil conditions) and management information (e.g., planting dates, fertilization, and cultivar choice). At a regional or global level, this information is often not available. However, some information can be obtained from FAO summary reports (e.g., soil characteristics and crop management information), but other information might have to be estimated (e.g., initial soil conditions). Stehfest et al. (2007) showed that the quality of input information varies with the sources and can have a significant impact on a global crop simulation. Sacks et al. (2010) used global information of planting and harvesting dates to determine the relationship between planting dates, temperature, precipitation, and potential evapotranspiration. They showed that for temperate regions this approach was reasonable, but not for the tropics and sub-tropics.

In general, crops are grown across many different climatic conditions and soil types, using different management strategies. But a critical aspect that affects productivity at any location or region is the type of cultivar. Cultivars have been bred for specific regions to take advantage of or mitigate specific environmental conditions. For example, in rainfed cropping systems, wheat has been selected for a specific flowering time, so it is late enough to avoid late frost and early enough to avoid terminal drought and heat stress (Richards, 2006). In crop models, cultivars are usually described by cultivar parameters representing their genetic potential. For example, cultivar parameter set rates for crop development, requirements for vernalization, sensitivity to photoperiod, and rates and limits for yield components. Despite the importance of cultivars in determining yields, Bondeau et al. (2007) used a process-based model with seven coefficients to discriminate between different crops, but ignored cultivar differences. Also, Nelson et al. (2010) simulated different crop species across environments worldwide to assess the impact of climate change on global food security, but did not consider the range of cultivars grown across regions. Similarly, other global climate change impact assessments simulated global crop production for a number of crops, but did not consider regional cultivar differences (Fischer et al., 2005; Parry et al., 1999; Balkovič et al., 2014). However, Sayre et al. (1997) clearly showed that different wheat cultivars perform differently in terms of growing processes even within the same environment. This is supported by many other field experiments throughout the world in which different cultivars were grown next to each other to determine cultivar-specific responses to growing conditions (Abdin et al., 1996; Jiang et al., 2000; Li et al., 2011; Lopes et al., 2012; Tripathi et al., 2004).

The international wheat-breeding network, facilitated by the International Maize and Wheat Improvement Center (CIMMYT), has categorized the wheat-growing regions of the world into 17 Mega Environments (MEs) based on agro-ecological zones (Monfreda et al., 2008). These agro-ecological zones are the target breeding regions that represent various growing conditions and disease pressures, but the latter is not considered in this study. Recent multi-model comparisons have shown large differences in crop model responses to climate change factors and stressed the importance of continuous crop model improvement (Asseng et al., 2013; Bassu et al., 2014). Model improvements include better routines, parameters, and inputs (Challinor et al., 2014), including regional cultivar-characterizations for global assessments. Climate change impact assessments compare a future scenario with a baseline or a crop grown under current conditions; hence, having a well-developed baseline that considers current cultivar differences is critical. The objective of this study was to develop and validate a global wheat production baseline simulation by considering ME-specific cultivars based on field experiments in order to improve global-scale simulations. As regional-specific cultivars have never been used in any global simulation study, the aim was to introduce and test a worldwide regional cultivar characterization as the foundation for improved future climate change impact assessments.

2. Materials and methods

2.1. Crop simulation model

Simulations of wheat cultivars were performed using the Decision-Support Systems for Agrotechnology Transfer (DSSAT) v 4.5, with CROPSIM-CERES v. 4.5.1.013 crop model for wheat to simulate crop growth and development (Hoogenboom et al., 2010). DSSAT is a process-oriented modeling framework that simulates daily crop growth and development as a response to environmental conditions (e.g., weather and soil), crop cultivar characteristics, and agronomic management.

The CROPSIM-CERES wheat model divides the growth and development processes into biomass growth, leaf expansion and growth, phase development, and morphological development. Each process is influenced by environmental factors and water and/or nitrogen stress (Ritchie and Otter-Nacke, 1985). Crop development rates are a function of the Growing Degree Days (GDD) calculated using daily maximum and minimum temperatures and a base temperature for wheat. The daily GDD is a trapezoidal function with the cardinal points representing base temperature, two optimal temperatures, and a maximum temperature above which crop development stops. The plant life cycle/crop development is divided into seven phases, including germination, emergence, terminal spikelet, ends ear growth, beginning grain filling, maturity, and harvest. Day length affects the total leaf number, which in turn affects floral initiation. Daily crop growth is calculated by converting the daily intercepted Photosynthetic Active Radiation (PAR) into crop biomass with a crop-specific radiation use efficiency parameter.

Kernel numbers are calculated during flowering as a function of a cultivar-specific potential (i.e., potential kernel growth rate) and crop growth before flowering to start of grain filling, which is affected by temperature and water and nitrogen stress factors. During grain filling, the model calculates a daily kernel growth rate as a function of a cultivar-specific potential grain-filling rate modified by temperature and assimilates supply.

2.2. Model inputs

2.2.1. Genetic parameter

User-specified cultivar parameters include photoperiod sensitivity (P1D); vernalization requirement (P1V); thermal time from the onset of linear grain filling to maturity (P5); kernel number per unit stem and spike weight at anthesis (G1); potential kernel growth rate (G2); tiller death coefficient (G3); and thermal time between appearance of leaves (PHINT).