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Considering sink strength to model crop production under elevated atmospheric CO_2

Eline Vanuytrecht[a,*], Dirk Raes[a], Patrick Willems[b]

[a] Division of Soil and Water Management, Department of Earth and Environmental Sciences, K.U. Leuven University, Celestijnenlaan 200E, P.O. 2411, B-3001 Heverlee, Belgium
[b] Hydraulics Laboratory, Department of Civil Engineering, K.U. Leuven University, Kasteelpark Arenberg 40, B-3001 Heverlee, Belgium

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ABSTRACT

Climatic changes and elevated atmospheric CO_2 concentrations will affect crop growth and production in the near future. Rising CO_2 concentration is a novel environmental aspect that should be considered when projections for future agricultural productivity are made. In addition to a reducing effect on stomatal conductance and crop transpiration, elevated CO_2 concentration can stimulate crop production. The magnitude of this stimulatory effect ('CO_2 fertilization') is subject of discussion. In this study, different calculation procedures of the generic crop model AquaCrop based on a foregoing theoretical framework and a meta-analysis of field responses, respectively, were evaluated against experimental data of free air CO_2 enrichment (FACE) environments. A flexible response of the water productivity parameter of the model to CO_2 concentration was introduced as the best option to consider crop sink strength and responsiveness to CO_2. By varying the response factor, differences in crop sink capacity and trends in breeding and management, which alter crop responsiveness, can be addressed. Projections of maize (*Zea mays* L.) and potato (*Solanum tuberosum* L.) production reflecting the differences in responsiveness were simulated for future time horizons when elevated CO_2 concentrations and climatic changes are expected. Variation in future yield potential associated with sink strength could be as high as 27% of the total production. Thus, taking into account crop sink strength and variation in responsiveness is equally relevant to considering climatic changes and elevated CO_2 concentration when assessing future crop production. Indicative values representing the crop responsiveness to elevated CO_2 concentration were proposed for all crops currently available in the database of AquaCrop as a first step in reducing part of the uncertainty involved in modeling future agricultural production.

1. Introduction

Global warming and concomitant climatic changes are unequivocal (IPCC, 2007). The Intergovernmental Panel on Climate Change (IPCC) anticipates an average increase of air temperature by 0.2 °C per decade in the coming years. Along with alterations in cloud cover, the evaporative power of the atmosphere will be affected. Changes in both the amount and pattern of precipitation are expected resulting in less predictable and more extreme droughts and floods (IPCC, 2007). Large efforts have been made to develop models and methods to generate projections of the future climate on a global and regional scale. However, uncertainty remains for the projections.

A principal cause for the climatic changes is the elevated atmospheric concentration of greenhouse gases. A steady increase of the atmospheric CO_2 concentration ($[CO_2]$) has manifested since the industrial revolution ($[CO_2] < 300\ \mu mol\ mol^{-1}$ in 1900) and will continue by approximately $2\ \mu mol\ mol^{-1}$ per year in the coming years. Without serious mitigation strategies, $[CO_2]$ will increase up to 560–600 $\mu mol\ mol^{-1}$ in 2100 (IPCC, 2007). Elevated $[CO_2]$ induces climatic alterations and has a direct effect on plant growth and soil water balance. Inevitably, these changes affect water resources and agricultural productivity worldwide with serious implications for food security.

Increases in mean seasonal temperature of only 2–4 °C and episodes of extreme temperatures will reduce crop yields when the optimal temperature ranges of crops are exceeded (Adams

Abbreviations: $[CO_2]$, atmospheric CO_2 concentration; *B*, cumulative dry aboveground biomass; CGC, canopy growth coefficient; EF, Nash–Sutcliffe coefficient of efficiency; ETo, reference evapotranspiration; FACE, free air CO_2 enrichment; FAO, Food and Agriculture Organization of the United Nations; GCM, global circulation model; GDD, growing degree days; HI, harvest index; IPCC, Intergovernmental Panel on Climate Change; KMI/RMI, Royal Meteorological Institute of Belgium; R^2, coefficient of determination; RRMSE, relative root mean square error; Tr, crop transpiration; WP*, normalized crop water productivity; *Y*, dry yield.

* Corresponding author. Tel.: +32 16 32 97 54; fax: +32 16 32 97 60.
E-mail addresses: Eline.Vanuytrecht@ees.kuleuven.be (E. Vanuytrecht), Dirk.Raes@ees.kuleuven.be (D. Raes), Patrick.Willems@bwk.kuleuven.be (P. Willems).

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et al., 1998; Battisti and Naylor, 2009; Wheeler et al., 2000). Altered rainfall patterns and evaporative power of the atmosphere will dramatically change the moisture availability for crops (Easterling and Apps, 2005; Lobell et al., 2008). The negative effects of the mentioned climatic modifications may be tempered or counteracted by the growth stimulating and water saving effects of elevated [CO_2] on plants (e.g., Arnell et al., 2004). Crop responses to elevated [CO_2] have been extensively studied. Results of individual experiments and meta-studies in enclosure facilities or free air CO_2 enrichment (FACE) installations agree on the occurrence of CO_2-induced stomatal closure and a stimulatory effect on photosynthesis and biomass production of C3 crops (e.g., Ainsworth and Long, 2005; Ainsworth and Rogers, 2007; Kimball et al., 2002). This stimulatory CO_2 fertilization effect is less obvious for C4 crops (Leakey, 2009). However, the decline in stomatal conductance, which leads to a (smaller than proportional) decline in crop transpiration and has a positive impact on crop water use efficiency, has been observed for both C3 and C4 crop types (Kimball et al., 2002; Leakey et al., 2009).

A lack of clarity remains with regard to the magnitude of the stimulatory CO_2 effect. First, there is a debate on the effect of the experimental system. Some authors have emphasized the inconsistency between the low responses in FACE environments and higher responses in (semi-)closed system studies (e.g., Ainsworth and Long, 2005; Ainsworth et al., 2008; Long et al., 2006), while others have stressed the similarity if responses are rescaled to comparable [CO_2] levels (e.g., Tubiello et al., 2007; Ziska and Bunce, 2007). Secondly, responses vary among studies (Kimball et al., 2002; Sun et al., 2009) because different crop species and cultivars exhibit different responses in addition to various environmental factors affecting the responses. Limited nitrogen availability decreases usually the response to elevated [CO_2], and water stress can increase the CO_2 stimulation (Kimball et al., 2002; Sun et al., 2009). The results of individual experiments have been assembled in meta-studies, which provide a general understanding that exceeds the knowledge from individual experiments. Sun et al. (2009) quantified the yield increase of C3 crops to be 18% on average, ranging from 3 to 35% under elevated [CO_2] in various FACE experiments. Ainsworth and Long (2005) applied specific meta-analytical techniques to quantitatively synthesize research results from independent experiments, and they found that crop yield increases between 10 and 25% in FACE environments.

The assembled information is valuable to adapt crop models to simulate crop growth and production under climate change (Rogers and Dahlman, 1993; Tubiello and Ewert, 2002). Crop models are valuable tools, and they have been used to assess the impact of diverse environmental factors on crop production (Benbi and Nieder, 2003; Boote et al., 1996). Several agricultural models for studies on global change have been adapted to include the CO_2 effect (for an overview see Tubiello and Ewert, 2002). The need for model adaptation is emphasized when yield projections under scenarios of climate change with and without considering elevated [CO_2] are compared (Parry et al., 2004). While yields generally decline under future weather conditions without consideration of elevated [CO_2], including the CO_2 fertilization effect drastically tempers the yield decline and improves the crop/water relations.

To study the impact of climate change on food security worldwide, generic models that can accurately simulate the responses of different key crops to diverse environmental conditions (including weather variables and [CO_2]) are valuable tools. For practical appraisals, simple crop models, which require few inputs and include a simplified summary of complex physiological or biochemical crop processes, are most useful (Jame and Cutforth, 1996; Todorovic et al., 2009). The crop water productivity model AquaCrop is such a simple generic model (Raes et al., 2009b; Steduto et al., 2009) and can be used to assess the impact of climate change on crop production. The model has been calibrated and validated in diverse environments for a range of crops with local to worldwide significance for food security (e.g., Farahani et al., 2009; Geerts et al., 2009; Hsiao et al., 2009). The growth engine of AquaCrop is water-driven and relates biomass production to crop transpiration via a conservative, crop-specific water productivity parameter. The normalization of this parameter for climate (i.e., reference evapotranspiration, ETo) and [CO_2] has to assure the applicability of the model in broad ranges of space and time (Steduto et al., 2007, 2009). To capture the variation of crop responses to elevated [CO_2], the model should include appropriate calculation procedures.

In this study, three different modeling procedures for AquaCrop to simulate crop responses to elevated [CO_2] are presented. The procedures included the adjustment of a water productivity parameter according to the following factors: (a) results of a theoretical study supported by pot experiments (Steduto et al., 2007); (b) results of a meta-analysis of crop responses in FACE environments; and (c) a flexible hybrid of the two former procedures with the introduction of a crop sink strength coefficient. The objectives of the study were to evaluate the model performance to simulate crop growth and production under elevated [CO_2] with each of the calculation procedures and to highlight the differences in crop production as a consequence of quantitative differences in the CO_2 fertilization effect. Finally, indicative values representing the crop sink strength were proposed for all crops currently available in the database of AquaCrop.

2. Materials and methods

2.1. Model description

Crop development in AquaCrop consists of simulating the development of green canopy (for water transpiration) and expansion of roots (for water uptake) under the governing environmental conditions (Raes et al., 2009b; Steduto et al., 2009). The expansion of the green canopy cover is described by a canopy growth coefficient (CGC), which is a conservative crop-specific parameter. Water, air temperature or soil fertility stress may hamper canopy expansion resulting in less crop transpiration.

In exchange for water transpired by the crop, aboveground biomass is produced. Cumulative aboveground biomass production (B) is obtained via summation of the daily ratio of crop transpiration (Tr) and ETo over the sequential days spanning the period when biomass is produced (Eq. (1)). Yield (Y) is the product of the final biomass multiplied by the harvest index (HI) (Eq. (2)). The following equations are used to calculate the biomass production and yield (Raes et al., 2009b):

$$B = \mathrm{WP}^* \cdot \sum_{i=1}^{n} \left(\frac{\mathrm{Tr}_i}{\mathrm{ETo}_i} \right) \qquad (1)$$

$$Y = \mathrm{HI} \cdot B \qquad (2)$$

where B is the cumulative aboveground biomass production (g m^{-2}); Tr_i is the daily crop transpiration (mm day^{-1}); ETo_i is the daily reference evapotranspiration (mm day^{-1}); n is the sequential days spanning the period when B is produced; WP* is the normalized crop water productivity (g m^{-2}); Y is the yield production (g m^{-2}); and HI is the harvest index.

ETo can be determined with the help of the FAO–Penman–Monteith method using meteorological data (Allen et al., 1998). The proportional factor (WP*) is water productivity normalized for [CO_2] and local climate (i.e., expressed by ETo). WP* is a crop-specific parameter that considers the crop water productivity for a reference [CO_2] of 369.41 μmol mol^{-1} (i.e., the average [CO_2] for the year 2000 measured at the Mauna Loa Observatory in Hawaii, US).