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Performance of the SUBSTOR-potato model across contrasting growing conditions

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A B S T R A C T

Crop models are essential tools in climate change impact assessments, but they often lack comprehensive field testing. In this study, we tested the SUBSTOR-potato model with 87 field experiments, including 204 treatments from 19 countries. The field experiments varied in potato species and cultivars, N fertilizer application, water supply, sowing dates, soil types, temperature environments, and atmospheric CO_2 concentrations, and included open top chamber and Free-Air-CO_2-Enrichment (FACE) experiments. Tuber yields were generally well simulated with the SUBSTOR-potato model across a wide range of current growing conditions and for diverse potato species and cultivars, including *Solanum tuberosum*, *Solanum andigenum*, *Solanum juzepczukii* species, as well as modern, traditional, early, medium, and late maturity-type cultivars, with a relative RMSE of 37.2% for tuber dry weight and 21.4% for tuber fresh weight. Cultivars 'Desiree' and 'Atlantic' were grown in experiments across the globe and well simulated using consistent cultivar parameters. However, the model underestimated the impact of elevated atmospheric CO_2 concentrations and poorly simulated high temperature effects on crop growth. Other simulated crop variables, including leaf area, stem weight, crop N, and soil water, differed frequently from measurements; some of these variables had significant large measurement errors. The SUBSTOR-potato model was shown to be suitable to simulate tuber growth and yields over a wide range of current growing conditions and crop management practices across many geographic regions. However, before the model can be used effectively in climate change impact assessments, it requires improved model routines to capture the impacts of elevated atmospheric CO_2 and high temperatures on crop growth.

1. Introduction

Potato is the most important non-grain crop worldwide with a production of 330 million tonnes globally in 2010 (FAO, 2010). Potato production has increased dramatically during the last decade in the developing world, surpassing the production levels of the developed world (FAO, 2010). Potato constitutes the main source of food security and income in the developing world (Lutaladio and Castaidi, 2009), and will become increasingly important as the population is growing more rapidly in the developing world than developed regions (Lutz and KC, 2010). A growing population, along with climate change and increasing climate variability, will put additional pressure on potato food systems. Assessing the implications of these trends requires integrating crop models when

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evaluating the impact of new technologies and strategies for adapting to climate change.

Atmospheric concentration of carbon dioxide (CO_2) is expected to increase from 400 ppm in 2010 to 550 ppm by 2050 (IPCC, 2013). Potato, a C3 crop, will respond with higher photosynthesis rate (Finnan et al., 2008) and water use efficiency under elevated atmospheric CO_2 concentrations (De Temmerman et al., 2002b; Fleisher et al., 2013). But high levels of atmospheric CO_2 are the main driver of climate change and will increase global temperature and higher rainfall variability, leading to heat waves and more droughts in some regions (IPCC, 2013). Studies in controlled experiment chambers suggest that elevated atmospheric CO_2 concentrations can mitigate stresses due to water shortage, but high temperatures can also negate the positive effects of increased atmospheric CO_2 concentrations on crop production (Kaminski et al., 2014).

Crop models are powerful tools that describe crop development and growth as a function of crop management, weather, and soil conditions (Haverkort and Top, 2011). More than 30 crop models have been developed for potato, and many of them have been used to study the impacts of climate change on potato production (Raymundo et al., 2014). Overall, these studies highlight that despite the positive effect of atmospheric CO_2 concentrations, potato production will decline across many regions in the world by 2100 (Raymundo et al., 2014). However, Stockle et al. (2010) indicated that, taking into account the effect of CO_2, adaptation strategies on crop production might guarantee the current production levels under future climate change conditions in the state of Washington in the United States. Others have used potato crop models to assess the impact of climate change on regional (Tubiello et al., 2002; Supit et al., 2012) and global potato production (Hijmans, 2003). Nevertheless, models have been developed for specific cultivars and geographic domains (Griffin et al., 1993; MacKerron, 2004). Global simulations require taking into account the crop variability across the globe and testing the model functionality with a standard cultivar across latitudes. In most of the climate change studies, potato models were used with cultivars and species from the developed world (Tubiello et al., 2002; Hijmans, 2003; Supit et al., 2012), neglecting the cultivar diversity of other cultivated species, as well as traditional and modern cultivars. Cultivars of the species *Solanum tuberosum* are most widely grown, whereas seven cultivated potato species, including *Solanum andigenum* (floury potato), and *Solanum juzepzukii* (bitter potato), coexist in the tropical Andes (Huaman and Spooner, 2002). Also, several hybrids of various species are grown in the developing world (Thiele et al., 2007), where the use of potato models is limited.

Most published potato crop models had limited exposure to field measurements for testing, and none of them have ever been tested with observed data under high temperature and drought conditions (Raymundo et al., 2014). Some potato crop models still ignore the effect of increasing atmospheric CO_2 concentrations on crop growth (Hijmans, 2003; Gobin, 2010; Saue and Kadaja, 2011). Most models include a theoretical C3 crop response to elevated atmospheric CO_2 (Raymundo et al., 2014), but only two potato models, LOPTCO and AQUACROP, were tested with experimental data of yield response to elevated levels of CO_2 concentrations (Wolf and Van Oijen, 2003; Vanuytrecht et al., 2011). The SUBSTOR-potato and the LINTUL-potato models are the most widely used models for climate change studies (Franke et al., 2013; Haverkort et al., 2013; Raymundo et al., 2014); however, both models lack model testing with experimental data under elevated atmospheric CO_2 concentration expected in the future. Currently, publications of model applications outnumber publications of model performance testing (Raymundo et al., 2014). Therefore, field testing with current and possible future scenarios is required to build confidence in any crop model application. The most extensive field potato experimental dataset from around the world has been assembled to evaluate the performance of the SUBSTOR-potato model to guide model improvement needs and support future model applications.

2. Material and methods

2.1. The model

The SUBSTOR-potato model belongs to a family of crop models in the DSSAT-CSM (Decision Support Systems for Agro-technology Transfer—Crop Simulation Model) software (Jones et al., 2003; Hoogenboom et al., 2012). The model inputs are daily weather data, soil profile parameters, cultivar parameters, and crop management information. The SUBSTOR-potato model simulates the daily dynamics of phenology, biomass, and yield accumulation. The model accounts for soil water deficit factors that reduce photosynthesis (SWFAC) and growth (TURFAC) (Ritchie et al., 1995). Similarly, the model uses a nitrogen deficiency factor (NFAC) computed by the actual leaf nitrogen content, the critical leaf nitrogen content and minimum leaf nitrogen content to reduce photosynthesis (NSTRES) and growth (AGEFAC). Under water or nitrogen stress, SWFAC and NSTRES hasten tuber initiation and increase the carbon demand of tubers. The model has been extensively described by Griffin et al. (1993), and Ritchie et al. (1995). Following is a brief summary of the model.

The SUBSTOR-potato model simulates five phenological stages, including (1) pre-planting, (2) planting to sprout elongation, (3) sprout elongation to emergence, (4) emergence to tuber initiation, and (5) tuber initiation to harvest. Five cultivar-specific parameters control crop development and growth. The parameters tuber initiation sensitivity to photoperiod (P2, dimensionless) and upper critical temperature for tuber initiation (TC, °C) affect phenology; and leaf area expansion rate (G2, $cm^2\ m^{-2}\ day^{-1}$), potential tuber growth rate (G3, $gm^{-2}\ day^{-1}$), and an index that suppresses tuber growth (PD, dimensionless) affect biomass accumulation (Griffin et al., 1993).

The SUBSTOR-potato model has different trapezoidal temperature impact functions, which simulate the effect of temperature on leaf growth (RTFVINE), root and tuber growth (RTFSOIL), photosynthesis (PRFT), and tuber initiation (RTFTI). Each of these functions has a range from zero to one. For RTFVINE, daily mean temperature is optimal between 18 °C and 24 °C and potential leaf expansion stops at <2 °C and >35 °C. For RTFSOIL, soil temperature (computed in the model from daily mean temperature) is optimal between 15 °C and 23 °C, and root and tuber growth stops at <2 °C and >35 °C. For PRFT, mean daily temperature is optimal between 15 °C and 30 °C, and photosynthesis stops at <3 °C and >42 °C. For RTFTI, a weighted average temperature is used (mean of 0.75 times the minimum temperature plus 0.25 times the maximum temperature) and is optimal between 10 °C and the upper critical temperature set with the cultivar parameter TC. Tuber initiation stops at <4 °C and >TC + 8 °C (Griffin et al., 1993).

2.1.1. Tuber initiation

Parameters TC and P2 play a key role at tuber initiation. If temperature is above TC, the tuber initiation and tuber bulking is reduced or inhibited. Thus, the upper value of TC can be interpreted as representing high temperature tolerance. P2 describes the sensitivity to day length and has a dimensionless value between 0 and 1. The closer P2 is to 0, the less sensitive a cultivar is to long photoperiods. Both parameters, TC and P2, are embedded in functions that determine the tuber initiation and influence tuber bulking.

The relative temperature function for tuber initiation (RTFTI) is described as follows:

$$\text{RTFTI} = 0; (\text{TEMP} <= 4)$$