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Simulating cultivar variations in potato yields for contrasting environments

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ABSTRACT

Potato (*Solanum tuberosum* L.) is a major food commodity becoming increasingly important for food security, especially in the developing world. The rising demand for potatoes combined with yield gaps and potential adverse impacts from climate change call for strategies for yield improvement and environmental adaptation. Crop growth models can help identify and assess such strategies. In this study, the SUBSTOR potato model was used in a systematic assessment of all cultivar parameters in the model in a range of environments including temperate, subtropical, and tropical regions to identify options for future crop improvement and to develop strategies for climate change adaptation in potato production. Our results show that yield responses to changes in cultivar parameters are specific to the environment. Some changes are less effective in subtropical and tropical environments and more effective in increasing yields in temperate environments. Solar radiation, day length, and temperature are the environmental factors that constrain the effectiveness of cultivar parameters in changing yields. The simulated variation in yields among environments was larger than the variation from changes in cultivar parameters. The impact of cultivar parameter changes on yield also varied with the cultivar parameter. The potential tuber growth rate was the cultivar parameter with the strongest effect on yields. Changes in the potential tuber growth rate parameter can lead to large yield changes in tropical highlands and temperate environments that have high solar radiation to ensure sufficient assimilate production for a larger sink. Results also suggest that improving crop management (e.g., N input) is more important for increasing yields than the potential in cultivar improvement. The study showed that crop modeling can help assess alternative strategies of yield improvement and support targeting and prioritization of efforts to improve crop productivity across different environments, based on an improved understanding of genotype by environment by management interactions. Results also showed how crop models can yield insights relevant for climate change adaptation even when only using weather data of the current climate.

1. Introduction

Potato (*Solanum tuberosum* L.) is the third most important food crop in the world (FAO, 2013) and is becoming increasingly important in the developing world. Potato is the one commodity in developing countries with consistent increases in quantities consumed per capita (Bruinsma, 2003). In 2006, production in developing countries equaled that of developed countries for the first time in recent history (Birch et al., 2012; Scott, 2002; Walker et al., 2011). The potato's role has steadily strengthened and is expected to grow as long as varieties resilient to the potential effects of climate change are available.

Potato will play an important role for future food security. For example, increased use of potato as a staple crop is extremely important in Africa, especially because of the strong predicted population increases (Birch et al., 2012). Potatoes are also grown in regions with high incidence of poverty, malnutrition, and food insecurity, such as the tropical highlands of Africa, the Andes of South America, and the Indo-Gangetic basin of southern Asia (Bruinsma, 2003; Thiele et al., 2010).

Potato production throughout the world is likely to be affected by climate change. Higher temperatures, changes in precipitation and water availability, and higher incidence of pests and diseases are expected to negatively impact crop yields and production (Haverkort and Verhagen, 2008). In a global modeling exercise, Hijmans (2003) estimated that the reduction in potential potato yields by 2070 could range between 9% and 32%. Production could increase at higher latitudes (over 50° North and South) and other regions where cold temperatures and frost have been a constraint. There are also positive effects of higher atmospheric CO_2 concentrations on yields (Conn and Cochran, 2006; Fleisher et al., 2008, 2013; Högy and Fangmeier, 2009; Miglietta

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et al., 1998; Schapendonk et al., 2000; Sicher and Bunce, 1999) and water use efficiency (Fleisher et al., 2008; Haverkort and Verhagen, 2008; Haverkort et al., 2013; Wheeler et al., 1999).

These anticipated future changes show the need to prepare for adaptation, particularly in regions where net effects of climate change are likely to be negative. Besides changing growing areas and crop and water management, breeding new cultivars is a principal way to adapt potato production to climate change (Haverkort and Verhagen, 2008). The most obvious traits to target when breeding potato for climate change adaptation are increased tolerance to high temperatures and drought, resistance to pests and diseases, and a reduced growing period through early maturity without yield reduction that will help avoid late-season unfavorable temperature conditions and pests and diseases.

The impact of variable and changing climatic conditions on new, improved crop cultivars and their performance under such conditions are still uncertain. However, field testing of breeding programs to reduce this uncertainty is restricted because field experiments can only be carried out when cultivars exist. Given the time lag between the identification of the need for climate change adapted cultivars and their development, such cultivars may not be available for field testing in the near future. Also, time and resource constraints may limit the ability of breeding programs to set up long-term multi-location trials to test new genotypes over a sufficiently wide range of environments. Even if the possibility for extensive field trials exists, short-term and location-specific field experiments may not represent the environmental variability encountered by farmers (Shorter et al., 1991). In this context, an analysis using crop growth models can make an important contribution to agronomy and crop breeding. Crop models can assist to identify, assess, and prioritize potential traits for environmental adaptation by creating “virtual” genotypes to explore the relationship between physiological traits and yields and genotype-environment interactions (Boote et al., 2001; Hammer and Vanderlip, 1989; Semenov et al., 2009). Crop models also serve as tools to complement field testing by extending the range of environments and providing information about the performance of new cultivars under environmental conditions different from those at the testing sites (Shorter et al., 1991).

A number of crop modeling studies have evaluated hypothetical expressions of crop traits. The most common approach is to vary cultivar parameters to mimic new genotypes. A range of crops has been investigated, including wheat (Asseng et al., 2002; Ludwig and Asseng, 2010; Luo et al., 2009; Martín et al., 2014; Semenov et al., 2009), groundnut (Challinor and Wheeler, 2008a,b; Singh et al., 2013), sorghum (Hammer and Vanderlip, 1989; Singh et al., 2014a), maize (Sinclair and Muchow, 2001), chickpea (Singh et al., 2014b), and soybean (Boote, 2011; Boote et al., 2003). Traits considered included crop growth and the crop life cycle (Asseng et al., 2002; Boote et al., 2003; Hammer and Vanderlip, 1989; Ludwig and Asseng, 2010; Luo et al., 2009; Martín et al., 2014; Semenov et al., 2009; Singh et al., 2013, 2014a,b), drought and heat tolerance (Martín et al., 2014; Semenov et al., 2009; Sinclair and Muchow, 2001; Singh et al., 2013, 2014a,b), and tolerance to nitrogen deficiencies (Martín et al., 2014). The results indicated variability in the effectiveness of traits (Asseng et al., 2002; Ludwig and Asseng, 2010; Martín et al., 2014; Semenov et al., 2009; Sinclair and Muchow, 2001; Singh et al., 2014a) and showed that the magnitude of the impact depends on the environment (Asseng et al., 2002; Hammer and Vanderlip, 1989; Ludwig and Asseng, 2010; Singh et al., 2013, 2014a,b).

Semenov et al. (2009) explored the performance of virtual wheat cultivars in water-limited environments across three levels of parameter values. Luo et al. (2009) simulated virtual maturity types of wheat across five parameter levels, and Boote et al. (2003) used the CROPGRO-Soybean model to analyze trait variation in attributes related to photosynthesis, life cycle, vegetative growth, partitioning and rooting. By changing cultivar parameter values over large ranges, they found that the marginal effect of a given change in a parameter is not constant but depends on the absolute value of that parameter. Some studies included several locations (Asseng et al., 2002; Hammer and Vanderlip, 1989; Ludwig and Asseng, 2010; Singh et al., 2013, 2014b), but were often limited in their parameter range.

There are fewer crop-model-based trait impact studies available for potato. Spitters and Schapendonk (1990) assessed breeding strategies for drought tolerance by varying maturity types and seven plant traits related to drought tolerance. A study by Jefferies (1993) also considered drought tolerance in Scotland. Hijmans et al. (2003) modeled heat tolerance in a global scale analysis of the impact of climate change on potato production by a shift in the temperature response curve of their model. This study showed that heat tolerance can have positive effects on potential yields in most regions of the world. Hijmans et al. (2003) assessed the effect of frost-resistant varieties in Peru and Bolivia through an increase in parameter values across six levels. Stöckle et al. (2010) tested the implications of different maturity classes on the impact of climate change on potato production in the USA. They found yield increases due to later maturity at several locations of a similar environment type. However, none of these studies has varied cultivar parameters in a potato simulation model across climatic regions to assess the potential to increase potato production as a basis for future adaptation to climate change.

The objective of this study was to identify options for future crop improvement and to develop potential strategies for climate change adaptation in potato production. The SUBSTOR potato model included in the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 2011) was used to explore the impact of cultivar variation on potato yields in contrasting climatic regions. The study builds upon and extends previous studies on potatoes and other crops through a systematic assessment of all traits represented by cultivar parameters in the model. For each of the cultivar parameters, a sensitivity analysis was conducted over a wide range of possible values to achieve the following: a) to capture gene by environment (G $\times$ E) (or cultivar) interactions across contrasting sites representing temperate, subtropical, and tropical environments in the Americas, Africa, and Asia; b) to explain possible physiological and environmental constraints in potato cropping systems; and c) to gain insights into the effectiveness of alternative breeding options in the potato crop. It is argued that combining contrasting environments under current climate conditions with simulations over a wide range of cultivar parameters in the sensitivity analysis can yield valuable insights in order to identify options for climate change adaptation.

2. Material and methods

2.1. The DSSAT–SUBSTOR model

The SUBSTOR-Potato model in the DSSAT system (Griffin et al., 1993; Jones et al., 1998; Singh et al., 1998; Wilkens et al., 2004) is a process-based model that describes the duration of phases in the life cycle of potato and the rates of growth of vegetation, roots, and tubers during each phase. Life cycle and growth are simulated in daily time steps based on inputs of weather, soil properties, including initial conditions, and management inputs. Environmental conditions for growth are captured by routines for soil water and soil nitrogen balances (Godwin and Singh, 1998; Ritchie, 1998). Soil temperature routines account for the impact of temperature on tuber growth and development. The model assumes that pest and diseases are controlled and nitrogen is the only limiting soil nutrient.

Griffin et al. (1993) and Singh et al. (1998) described the functions used to simulate growth and development processes, and the functions are summarized for this paper, with emphasis on the cultivar parameters used to describe the genetic diversity of potatoes.

Plant development is divided into five phenological stages: pre-planting, planting to sprout germination, sprout germination to emergence, emergence to tuber induction, and tuber induction to maturity. The growth stages from emergence to maturity are the most relevant