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Modeling climate change impact on potato crop phenology, and risk of frost damage and heat stress in northern Europe

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ABSTRACT

Potato (*Solanum tuberosum*) is one of the main food crops in northern Europe, considered to be the fourth most important crop on a global scale after rice, wheat and maize. Climate change leading to longer growing seasons may call for adjustments in timing of planting and harvesting, and in this modeling study we assess potential effects of a warmer climate on potato crop phenology and temperature stress. A phenological potato model was parameterized with three planting dates to assess management impact on the timing of emergence and maturation of both early and late potato. Estimates on phenological development and occurrence of temperature stress were analyzed by comparing two developmental thresholds (0 °C and +2 °C) and three temperature response functions. The potato model was driven by observed gridded climate data and two sets of bias corrected climate model data, representing RCP4.5 and RCP8.5 for the period 1991–2100.

The future simulations indicated that a warmer climate and earlier planting may move the timing of harvest up to 1 month earlier, however, potato emergence early in the year will be associated with an increased risk of frost damage in most parts of northern Europe. The areas of west Europe most prone to frost damage today may experience a risk of frost damage in response to climate change. The simulation of early potato development was sensitive to the setting of the developmental threshold, while late potato development was sensitive to the optimum temperature setting. While a linear temperature response function is essentially sufficient for current climate conditions in northern Europe, optimum and upper thresholds should be considered in climate change impact assessments. The potato model runs with temperature data corrected according to quantile-mapping indicated in general a slightly higher risk of temperature stress than the corresponding runs with temperature data corrected by linear scaling.

1. Introduction

Climate change is expected to threaten the food security globally as the consequences of the rising temperature of the earth becomes evident (Parry et al., 2004). According to climate model projections, the global average air temperature is likely to increase with 0.3–4.8 °C by the end of this century (IPCC, 2013). Several recent studies have evaluated the effect of climate change on agriculture production through assessing its sensitivity and vulnerability at the regional (Iglesias et al., 2009; Maracchi et al., 2005; Miraglia et al., 2009; Supit et al., 2012) and global scale (Hijmans, 2003; Rosenzweig et al., 2014).

The European agriculture sector is considered to be one of the world's largest food producer (Olesen et al., 2011). Climate change and its impact on agricultural production in Europe will differ across regions, depending both on direct (i.e. abiotic) effects of changing climate conditions on crop yields and on indirect (i.e. biotic) effects caused by increased pressure from pests and pathogens (Olesen and Bindi, 2002; Olesen et al., 2011; Porter and Semenov, 2005). In south Europe, the productivity will likely decline as climate gets drier and warmer (Supit et al., 2012), whereas the agriculture at higher latitudes may benefit from an extension of the growing season (Peltonen-Sainio et al., 2009).

Potato (*Solanum tuberosum* L.) is an important crop worldwide, and it is considered to be the fourth most important crop after rice, wheat and maize (FAO, 2008). Early potato varieties are used as fresh food, whereas late potato varieties are used for processing, i.e. production of French fries and potato chips. Potato cultivars originated from the cool temperature Andean region of South America (Hawkes and Franciscoortega, 1993), and were introduced to Europe in the beginning of the 16th century (Ruiz de Galarreta et al., 2006). Due to its origin, potato grows best in cool climate during the frost free season and does not perform well in heat (Haverkort and Verhagen, 2008). Temperature is the main factor

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controlling the phenological development of potato (Kooman and Haverkort, 1995), and crop growth models have been developed to account for the temperature effect using either an empirical approach (Hagman and Mårtensson, 2013; MacKerron and Waister, 1985; Sands et al., 1979; Wolf and Van Oijen, 2003) or a process-based approach (Kooman and Haverkort, 1995; Streck et al., 2007; Wolf, 2002).

Recent development of climate models have led to an improved representation of weather and climate extremes, making it possible to take abiotic stress factors into account when simulating biotic responses (Jönsson et al., 2015). Climate change impact assessments are nevertheless associated with uncertainties from a range of sources, such as impact model parameterization, choice of climate model data and future scenario assumptions (Refsgaard et al., 2013). Bias correction of global and regional climate model data is commonly needed though it is generally difficult to interpret the effect in terms of uncertainty reduction (Ehret et al., 2012). Different species have different environmental requirements, which in turn influence how sensitive a specific impact study will be to uncertainties in climate data (Chokmani et al., 2001).

The aim of this modeling study was to assess potential effects of a warmer climate on potato crop phenology and temperature stress in Europe, and to assess the sensitivity to model parameterization and climate model data uncertainties. A phenological potato model was parameterized with three planting dates to assess management impact on the timing of emergence and maturation of both early and late potato, and the associated risk of frost damage and heat stress. The potato model was driven by observed gridded climate data and two sets of bias corrected climate model data, representing RCP4.5 and RCP8.5 for the period 1991–2100, and the sensitivity to model parameterization was analyzed by comparing two developmental thresholds and three temperature response functions.

2. Materials and methods

A temperature dependent phenological Potato Model (PM) was developed in Matlab (2010b) to assess climate and management impact on the potato crop phenology in northern Europe. The model was driven by daily temperature data to calculate the date of potato emergence and maturity. Estimates on phenological development and occurrence of temperature stress were analyzed by comparing two developmental thresholds (0 °C and +2 °C) and three temperature response functions: (i) linear response above the developmental threshold; (ii) linear response until an optimum threshold is reached, and (iii) including also an upper temperature threshold above which no development occurs. Model simulations were carried out with three planting dates: January 1st (Day Of the Year 1), April 10th (DOY100) and May 1st (DOY121). January 1st was applied to assess the earliest potential timing of emergence, associated with the highest risk of frost damage. April 10th and May 1st represent current planting time in Scandinavia of early and late potato, respectively.

2.1. Climate data

The PM simulation required daily minimum (T_{min}) and mean (T_{mean}) temperature as an input. Daily temperatures were obtained from two climate datasets: (i) The European gridded observational dataset (E-OBS, version 9) covering period 1991–2010 (Haylock et al., 2008), and (ii) RCA4-EC-Earth by two Representative Concentration Pathways, RCPs (Moss et al., 2010) corresponding to radiative forcing by the end of the 21st century of 4.5 W/m^2 (Clarke et al., 2007), and 8.5 W/m^2 (Riahi et al., 2007). The chosen climate data sets have the same spatial resolution of 0.44° × 0.44°. PM simulations with climate model data were split into three periods: 1991–2010 (reference period), 2020–2050 (near future) and 2071–2100 (far future).

Several linear and non-linear bias correction methods are available (Teutschbein and Seibert, 2012), and in this study we compare two approaches, linear-scaling and quantile-mapping. In linear-scaling, a bias correction factor is calculated for each month. This is estimated as the grid-cell specific difference between the observed and simulated monthly mean temperatures. The correction factors are added to the climate model data to generate corrected daily time series. In this approach, the variability of the climate model data is not adjusted. The quantile-mapping corrects for differences in the distribution functions, and do therefore adjust the mean as well as the variance of the climate model data (Themeßl et al., 2012; Wilcke et al., 2013).

2.2. Potato developmental threshold

Potato has been grown in different geographical regions, and each region has its own varieties that are adapted to the local climate condition (Marinus and Bodlaender, 1975). The environmental and physiological factors that influence the potato development in different geographical areas under different temperature conditions have been documented in several studies (Table 1). Temperature and photoperiod are considered to be the two most important factors influencing the potato growth (Kooman and Haverkort, 1995). In northern Europe, where potatoes are grown during summer, the photoperiod is generally not restricting the development during the growth season. A range of variety specific temperature thresholds has been identified for describing the phenological development (Table 1); varying between 0–5 °C for the developmental threshold and 13–24 °C for the optimum temperature. Temperature above 25–30 °C have been found to promote leaf senescence (Kooman and Haverkort, 1995; Raes et al., 2012). For some varieties temperatures above 30 °C are likely to induce a major loss of productivity, i.e. in Polish potato varieties (Rykaczewska, 2013). However, a field study showed that maximum temperatures above 30 °C can be advantageous for potato varieties grown in Israel (Arazi et al., 1993).

2.3. Phenological potato model (PM) parameterization

In this study, we assessed the early and late potato phenology response to climate change using daily temperature data as input into the PM. The calculations of the phenological parameters emergence and maturation were based on the concept of thermal time (Trudgill et al., 2005). Daily mean temperatures above a developmental threshold (D.T.) were summed over the growing season, and the resulting daily accumulation of degree days (DD) were used for model assessment of the phenological development of the potato.

In the present study, we compared model runs with two developmental thresholds for calculating thermal time from planting to emergence and maturity in Europe; 0 °C (Hagman and Mårtensson, 2013) and +2 °C (Kooman and Haverkort, 1995; Raes et al., 2012; Supit et al., 2012). The PM was parameterized with four temperature response functions to calculate the temperature dependent phenological development (Fig. 1). M1 and M2 are linear models based on a developmental threshold of 0 °C (M1) and +2 °C (M2). In M3 the lower and optimal thresholds were set to +2 °C and +17 °C, respectively. That is, the model assumes a constant maximum development for days with a daily mean temperature above +17 °C (e.g., add 15DD when D.T. is +2 °C). The lower, optimal and