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Modeling potato root growth and water uptake under water stress conditions

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ABSTRACT

Potato (*Solanum tuberosum* L.) is considered a drought sensitive crop. Accurate simulation of root growth is critical for estimating water uptake dynamics. However, data required to build and test advanced potato root simulation approaches is lacking. Previously unpublished data from our soil–plant–atmosphere-research (SPAR) chambers was used to evaluate a new two-dimensional diffusive root growth module linked to the existing potato model SPUDSIM. The root module consisted of diffusive parameters controlling the direction of root growth in horizontal and vertical directions, and an additional convective term for vertical growth within the soil. This modified SPUDSIM was tested against observed SPAR data which consisted of root distribution in the soil profile and organ dry weights (DW) at harvest, plus daily water uptake patterns for each of six different irrigation treatments. The difference between simulated and observed DW data was within two standard errors for most plant organs—root DW was over-predicted for well-watered plants. Spatial and temporal patterns of root distribution and water contents were reproduced well. However, the model tended to over-estimate water uptake from soil layers closer to the surface. Differences in simulated root growth patterns among irrigation treatments were the result of fluctuations in soil water status, bulk density, and root density which, in turn, affected the amount of carbon allocated to the roots in different soil layers and the value of the convective term. These results suggest the new module will provide more reliable predictions of potato water uptake for improved agricultural decision support tools.

1. Introduction

Potato is one of the major crops worldwide and the United States of America was the fifth largest producer in 2010 in terms of total yield, and the third largest producer in terms of total value (FAO Statistical Yearbook 2012, http://faostat.fao.org/site/339/default.aspx). The potato plant is sensitive to drought and therefore susceptible to changes in climate and weather oscillations (van Loon, 1981). One response of crops to water or nutrient stress is to grow more roots in order to access more resources in the soil (Lynch, 2007). Another answer can be seen in root plasticity, where roots grow toward available water or nutrients (Hodge, 2004).

In their comprehensive review, Munoz et al. (2005) report that there is relatively little literature on potato root characteristic, water use and uptake of nutrients. Consequently, not much development has occurred in potato root modeling. Several potato crop models such as SUBSTOR (International Benchmark Sites Network for Agrotechnology Transfer, 1993), SIMPOTATO (Hodges et al., 1992), POTATO (Ng and Loomis, 1984), and others have been developed with the intent to improve field management operations. These crop models incorporate one-dimensional root models, and root growth rate is proportional to leaf growth and influenced by pre- and post-tuber initiation growth stages. Gayler et al. (2002) combined a model describing water, carbon and nitrogen fluxes on the field level with a plant model originally developed for winter wheat. The root growth module was based on CERES-Maize (Jones, 1986), which simulates roots length and density per soil layer as a one-dimensional step-wise distribution. Carbon was assigned to the roots based on water status of the soil (less carbon was assigned when soil water decreased below a critical level) and empirical weighting factors for every soil layer.

In a two dimensional root model, root density changes with depth and distance from the plant stem. This was implemented for a radial coordinate system by Vrugt et al. (2001a) who coupled HYDRUS-2D (Šimůnek et al., 1999) with the exponential root

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distribution model of (Raats, 1974) and modeled water uptake around an almond tree. Root growth and proliferation in two dimensions along a finite element grid with radial or rectangular coordinates was simulated by Acock and Pachepsky (1996). The authors implemented root proliferation estimated as a diffusion equation with a convective term accounting for gravitropism (plant roots growing downwards) into the modular soil and water model 2DSOIL (Timlin et al., 1996). The model was tested for experimental data (potted chrysanthemum plants) taken from Chen and Lieth (1993) and for maize grown in pots (Reddy and Pachepsky, 2001) and gravitropism was found not to influence root growth, probably due to the small pot size with a height of 7.5 cm. Willigen et al. (2002), Heinen et al. (2003) and Pronk et al. (2002) followed this approach of describing root densities per soil volume rather than simulating single roots and their branching patterns. These authors simulated one root class while Acock and Pachepsky (1996) and Reddy and Pachepsky (2001) distinguished between young and mature roots.

Implementing root architectural features into a density model is described by Dupuy et al. (2010a) and (2010b). The root system was simulated as three distinct density distributions of root apical meristems, root length, and root branching. New roots grow and branch from the apical meristems with specific elongation and branching rates. A similar approach of modeling root growth as spatial changes in root tip density was used by Bastian et al. (2008), who included nutrient uptake and changes in external and internal nutrient concentration in their model on hairy root networks. Bonneu et al. (2012) combined three operators describing advection as root tip growth along a defined direction, diffusion as growth in any direction and reaction as branching and mortality rates. The authors calibrated their model toward fine root growth around a main branch of horizontally growing eucalyptus roots.

In addition to one- and two dimensional root growth models as described above root growth can be simulated in three dimensions. Vrugt et al. (2001a, b) compared a root density model in one, two and three dimensions and found that estimating root water uptake in three dimensions is of advantage when small amounts of drainage outflow which can carry high concentrations of a nutrient or contaminant should be quantified. In addition, modeling root growth in three dimensions has the advantage to explicitly account for root morphology. Doussan et al. (1998a) developed a three dimensional architectural root growth model for maize based on work of Pagès et al. (1989). Root architecture was simulated for a network of root segments, each with a direction and velocity of growth. To account for water uptake the root model was later coupled to a soil water transport model following Clausnitzer and Hopmans (1994) and Doussan et al. (2006). Water and solute uptake by the roots was coupled to the soil model over sink terms of the water and solute equations. Another architectural root model, SimRoot, was developed by Lynch et al. (1997). It simulates maize and bean root systems, among others, based on an approach similar to Doussan et al. (1998b). SimRoot was later linked to SWMS_3D (Šimůnek et al., 1995; Postma and Lynch, 2011a, b) to account for nitrate uptake by maize roots. Three-dimensional architectural models are mainly used when the influence of root morphology on soil resource acquisition is investigated, while a two-dimensional density model as used in the present study can adequately describe water and nutrient uptake from different soil layers.

There are conflicting reports in literature about the rooting depth of potato. While some authors report it a rather shallow rooting crop (Opena and Porter, 1999), others observed potato roots reaching considerable depth in the soil profile. Vos and Groenwold (1986) found rooting depth down to 100 cm below hills in a marine-clay soil. Stalham and Allen (2001) observed that later in the season root systems of non-irrigated potato crops relying on water from deep soil horizons grew deeper compared to irrigated potato crops. Roots of non-irrigated crops were sparser in surface horizons, and the root length density (RLD) decreased less with increasing soil depth. The maximum rooting depth differed substantially with potato variety and reached 90–120 cm. Ahmadi et al. (2011) found rooting depths of potato down to 141 cm in loamy sand.

The effect of drought on carbon partitioning to the roots was investigated experimentally for wheat grown in a greenhouse by Gregory et al. (1995). They found the root:total DW proportion to be about 0.08 higher for plants grown with half the soil water content compared to well-watered plants, starting with 0.48 of total carbon incorporated into the roots of water stressed plants at an early growth stage. The root:total DW proportion decreased over time for both treatments. It is not clear whether potato roots respond the same way. The effect of drought on the potato root system was investigated experimentally by Opena and Porter (1999), who sampled root distribution under rain-fed and under supplementally irrigated plots over two years on a sandy soil in Florida. The observed root length densities did not change with irrigation treatments, but root DWs increased in the plots that received supplemental irrigation in the second year, when the authors used a finer mesh to collect roots.

The objectives of this work were (1) to improve the estimates of root growth and water uptake by roots under different drought conditions in the existing potato root growth model SPUDSIM and (2) to test the model performance against experimental data and evaluate its sensitivity to parameters that influence root growth. To achieve objective (1), a diffusive root growth model which simulates two dimensional root distributions in the soil profile was developed and integrated with the crop model SPUDSIM. To achieve (2), potato data, including root distribution, was analyzed from a six soil–plant–atmosphere-research (SPAR) chamber drought study from which one chamber was used for model calibration and the remaining data used for evaluation and sensitivity testing.

2. Material and methods

2.1. SPUDSIM and 2DSOIL models

The potato model SPUDSIM (Fleisher et al., 2010) is an explanatory crop model coded in C++ that simulates potato growth, development and yield on an hourly basis as influenced by environment, management, soil, and genetic inputs. SPUDSIM was integrated with 2DSOIL (Timlin et al., 1996) to simulate subsurface processes including root growth, water, solute, heat, and gas movement. Photosynthetic and transpiration rates and stomatal conductance are simulated using a leaf-level energy balance that is influenced by solar geometry, temperature, radiation, carbon dioxide (CO_2) concentration, leaf water potential, and plant nitrogen status. Potential growth rate and carbon allocation to individual organs (leaf, stem, tuber, and root) is dependent on carbon availability and developmental stage, itself sensitive to temperature and genetics. Actual growth of leaves, stems, and tubers at each time-step is further modified by plant nitrogen, water status, and root growth demand. Carbon allocation can be decreased to the canopy, and increased to the roots, at each time-step based on the ability of the roots to meet the crop transpiration demand. This dynamic is detailed in Section 2.1.1. Simulation of root growth and water uptake is handled by 2DSOIL, mainly because water and nutrient uptake by the roots are included as sink terms into the Richards (Richards, 1931) and the solute transport equations. In 2DSOIL, water, solute and heat transport is solved numerically using a two-dimensional finite element grid representation of the soil profile (Šimůnek et al., 1994). The grid, or mesh, is described using a set of nodes (analogous to a (x,y) Cartesian coordinate system) representing depth in the vertical (z) direction below the plant