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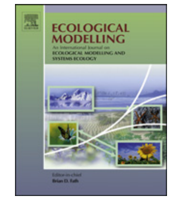

Modeling biopore effects on root growth and biomass production on soils with pronounced sub-soil clay accumulation

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ABSTRACT

Soils with subsoil clay accumulation account for more than 20% of the global land surface. These soils are characterized by vertical differences with respect to soil texture and increasing bulk density below the topsoil, which in turn affects root penetration into the subsoil. Biopores are preferential pathways for roots and assist in overcoming physical barriers like high density soil layers. An integration of these relationships into cropping systems models at the field scale is on-going. This paper presents a new approach to model the effect of biopores on root development in soils with clay accumulation at the plot scale. In this approach, the effect of biopores on root elongation rate depends on bulk density and on a biopore-root growth threshold (MPRT), which is the biopore volume at which the resistance of soil strength to root penetration is completely offset by the density of the biopores. The approach was integrated into a model solution of the model framework SIMPLACE (**S**cientific **I**mpact assessment and **M**odeling **PL**atform for **A**dvanced **C**rop and **E**cosystem management). MPRT was parameterized for spring wheat using the inverse modeling approach based on root observations from a multi-factorial field experiment on a Haplic Luvisol. The observed biopore densities (>2 mm diameter) were between 300 and 660 pores m^{-2} (equivalent to a volumetric proportion of 0.38–0.83%) depending on the preceding crop. Observed soil bulk densities ranged between 1.31 and 1.62 $g\,cm^{-3}$. For spring wheat, the best fit between simulated and observed root densities in different layers was obtained with a MPRT of 0.023 $m^3\,m^{-3}$ (equivalent to 2.3% of soil volume). The mean simulated total above ground biomass was sensitive to MPRT and had the best agreement with observed values when a MPRT between 0.023 and 0.032 $m^3\,m^{-3}$ was used in the simulations. Scenario simulations with the parameterized model at the same site demonstrate the importance of biopores for biomass production of short-cycle spring wheat when prolonged dry spells occur. The simulations allow a rough quantification of the biopore effects with respect to root elongation rate and biomass production at the plot scale with the potential to be extended to the field scale.

1. Introduction

In recent decades, significant progress has been made in the modeling of crops including root growth. The focus of many modeling efforts was on simulating the response of crops to diverse climate, soil and management conditions, e.g. CropSyst (Stockle et al., 2003), DSSAT (Jones et al., 2003), APSIM (Keating et al., 2003a), STICS (Brisson et al., 2003a) and the different models developed at Wageningen University (van Ittersum et al., 2003). However, most models consider effects of soil structural properties in a simplified way, using mainly soil bulk density as a proxy for penetrability of the soil layers (Keating et al., 2003b; Williams and Izaurralde, 2005). Soil bulk density affects simulated root penetration rates and in some cases extension of lateral roots (Brisson et al., 2003b). In soils with little vertical differentiation of bulk density and low macropore density, this simplification may yield satisfactory results when simulating root growth and development. However, in soils with pronounced vertical differences with respect to soil structure and macropore density, such simplified assumptions may lead to uncertain rates of root growth and of water and nutrient uptake. This is due to the fact that macropores generated by roots do not reduce soil bulk density, because the reduction of density in the voids created by the roots is largely compensated by the increased soil density of the root channel walls (Hirth et al., 2005; Young, 1998). Vertical differences with respect to soil texture and bulk density are characteristic features of soil types with clay accumulation

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like Luvisols, Alisols, Acrisols, Lixisols, Albeluvisols, and Nitisols. Besides, soils belonging to the soil group Planosols, are characterized by abrupt texture changes within the soil profile, mostly due to lithological heterogeneities. These seven soil groups together account for more than 20% of the global land surface (FAO, 2003). Luvisols, and in particular those derived from loess, are among the most intensively cropped soils in Central, Southern and Eastern Europe (FAO, 2003). Therefore, the influence of soil structure (porosity, pore size distribution) on root distribution patterns of food crops needs to be investigated and modeled (Wang and Smith, 2004).

Biopores are round-shaped biopores created by soil animals and decaying plant roots (Hirth et al., 2005). The importance of biopores as preferential pathways for roots to overcome physical barriers like high density soil layers has frequently been stressed (Stirzaker et al., 1996b; Volkmar, 1996). However, little work has been done to integrate such responses into plant and crop models. In some cases biopore effects on root growth and soil water dynamics have been investigated at the pot scale (Stirzaker et al., 1996a) or integrated into soil water balance models (Bronstert and Plate, 1997; Jakobsen and Dexter, 1987) but integration of these relationships into cropping systems models and model testing at the plot and field scale is on-going. Wu et al. (2007) developed a field scale model which combines model components for plant growth and development, nitrogen and carbon cycling as well as soil water dynamics with a three-dimensional root system sub-model as an interface. However, the interaction between soil structure and root development follows the simplified approach of other field scale crop models.

In this study, an attempt is made to model the effect of biopores on root development in a soil with subsoil clay accumulation. A new approach is proposed which is applicable at the plot scale with the potential to be extended to the field level. The approach has been integrated into a crop model solution of the model framework SIMPLACE (**S**cientific **I**mpact assessment and **M**odeling **PL**atform for **A**dvanced **C**rop and **E**cosystem management). We first describe the modeling approach and the implemented crop model solution in SIMPLACE as used in this study. Then, we present the parameter optimization procedure for spring wheat at the plot scale, using inverse modeling based on root observations from a multi-factorial field experiment in Germany. Finally, we apply the calibrated model, to demonstrate, via a sensitivity analysis, the importance of biopores for root growth, water and nutrient uptake as well as biomass production of drought stressed spring wheat.

2. Model development

2.1. The modeling framework SIMPLACE

SIMPLACE (**S**cientific **I**mpact assessment and **M**odeling **PL**atform for **A**dvanced **C**rop and **E**cosystem management) is a modeling framework which is based on the concept of encapsulating the solution of a modeling problem in discrete, replaceable, and interchangeable software units called SimComponents or sub-models (Enders et al., 2010). This structure of the model allows for an easy plug-in of new sub-models and the use of different approaches for the simulation of processes via alternate mathematical formulations. Presently, SIMPLACE contains sub-models for the major processes affecting crop growth (including root growth), i.e. (1) crop phenology and development, (2) shoot growth, (3) crop nitrogen demand, (4) crop water demand, (5) root growth, (6) soil temperature dynamics, (7) soil water dynamics and root water uptake, (8) soil carbon and nitrogen turnover and (9) soil mineral nitrogen dynamics (N uptake and N leaching) (Table 1). In addition, a flexible vertical soil discretization was implemented, allowing to accounting for different pore systems in the individual soil layers. For the current model application a layer thickness of 0.03 m was chosen as recommended by (Addiscott and Whitmore, 1991).

2.2. The model solution

A specific combination of sub-models within the framework is a model solution. For the purpose of this paper the solution SIMPLACE<Lintul2,STMPsim,SlimRoots,Hillflow,SoilCN> has been used, consisting of the combination of the sub-models Lintul2, SLIMRoots, Hillflow and SoilCN (Fig. 1 and Table 1). In this solution of SIMPLACE crop growth and development is solved by the LINTUL2 sub-model (van Oijen and Lefelaar, 2008), which has frequently been used and validated (Farre et al., 2000; Gimplinger and Kaul, 2009; Shibu et al., 2010; Wolf et al., 2002). In LINTUL2, crop development is driven by mean air temperature and crop specific base temperature. Carbon assimilation and crop growth rate depend on photosynthetic active radiation, leaf area index (LAI) and crop specific light use efficiency (LUE) according to the following equation:

$$\mathrm{GTOTAL} = \mathrm{LUE} \times \mathrm{PARINT}$$

where GTOTAL is the potential daily crop growth rate ($\mathrm{g\,m^{-2}\,d^{-1}}$) and PARINT is the intercepted photosynthetic active radiation ($\mathrm{MJ\,m^{-2}}$).

GTOTAL is reduced when root available soil water does not meet crop transpirational demand. In addition, nitrogen stress is considered as a growth constraint and affects LAI development, specific leaf area (and hence PARINT) as well as light use efficiency according to the approach used in LINTUL3 (Shibu et al., 2010). The assimilates are distributed to plant organs (leaves, stem, storage organs and roots) according to crop and development specific partitioning tables (Angulo et al., 2013; van Oijen and Lefelaar, 2008).

The soil in this SIMPLACE solution is subdivided into 50 layers with a thickness of 0.03 m each. In the SlimRoots sub-model, root growth is separated into the growth of seminal and lateral roots (Addiscott and Whitmore, 1991). In the original approach, maximum growth of seminals (ASROOTMAX in $\mathrm{g\,m^{-2}\,d^{-1}}$) is limited by the specific weight of seminals (WSROOT in $\mathrm{g\,m^{-1}}$) and a maximum penetration rate SROOTRATEMAX being set to 0.015 $\mathrm{g\,m^{-1}}$ and 0.033 $\mathrm{m\,d^{-1}}$ respectively for summer wheat (Bingham and Wu, 2011; Jamieson and Ewert, 1999; Pritchard et al., 1987):

$$\mathrm{ASROOTMAX} = \mathrm{SROOTRATEMAX} \times \mathrm{WSROOT} \times \mathrm{SROOTN}$$

with SROOTN being the number of seminals per squaremeter ($\mathrm{m^{-2}}$). The actual seminal growth (ASROOT) is limited by the supply of assimilates from the shoot (RWRT in $\mathrm{g\,m^{-2}}$) and the root penetration velocity related to the soil temperature in the deepest soil layer with roots (TCRATE in $\mathrm{m\,d^{-1}}$) according to (Jamieson and Ewert, 1999) with

$$\mathrm{ASROOT} = \mathrm{TCRATE} \times \mathrm{WSROOT} \times \mathrm{SROOTN}$$

The growth of lateral roots in the layers with seminal roots is determined by the soil water content in each layer and the assimilates (RWRT) provided by the shoot (minus assimilate consumption ASROOT by the seminals), establishing a feedback between soil available water and nitrogen on the one hand and shoot and root growth on the other hand. In order to take into account vertical differences in soil structure especially in soils with clay accumulation like Luvisols, the effect of soil strength on root growth has been incorporated into the SlimRoots sub-model (see next section).

Soil temperature fluctuation in each soil layer depends on the soil surface temperature (including the effect of snow cover and crop cover), the distance of the layer from the soil surface and the damping depth, where soil temperature is equal to the annual