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Tree root systems competing for soil moisture in a 3D soil–plant model

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ABSTRACT

Competition for water among multiple tree rooting systems is investigated using a soil–plant model that accounts for soil moisture dynamics and root water uptake (RWU), whole plant transpiration, and leaf-level photosynthesis. The model is based on a numerical solution to the 3D Richards equation modified to account for a 3D RWU, trunk xylem, and stomatal conductances. The stomatal conductance is determined by combining a conventional biochemical demand formulation for photosynthesis with an optimization hypothesis that selects stomatal aperture so as to maximize carbon gain for a given water loss. Model results compare well with measurements of soil moisture throughout the rooting zone, of total sap flow in the trunk xylem, as well as of leaf water potential collected in a Loblolly pine forest. The model is then used to diagnose plant responses to water stress in the presence of competing rooting systems. Unsurprisingly, the overlap between rooting zones is shown to enhance soil drying. However, the 3D spatial model yielded transpiration-bulk root-zone soil moisture relations that do not deviate appreciably from their proto-typical form commonly assumed in lumped eco-hydrological models. The increased overlap among rooting systems primarily alters the timing at which the point of incipient soil moisture stress is reached by the entire soil–plant system.

1. Introduction

Background: Forest ecosystems provide many economic, ecological and social benefits [1] and play a key role in regulating the energy, carbon, and water fluxes between the biosphere and the atmosphere. Soil water is extracted by plant roots, flows through the plant vascular system and evaporates from the plant leaves thus providing a bridge in which soil water reservoir and atmospheric water vapor concentration interact. Root water uptake (RWU) controls the water dynamics in the subsurface, thereby affecting plant water availability [2], soil water content [3], and the partitioning of net radiation into latent and sensible heat fluxes thereby impacting atmospheric boundary layer dynamics [1,4,5]. Yet, despite its documented importance, a number of thorny issues remain when representing RWU in hydrological and atmospheric models [6], and addressing a subset of these issues frames the compass of this work. Among the least studied of these issues is the representation of RWU when competition among trees for available root-water occurs. Such competition is rarely accounted for in conventional ecological and hydrological models. Earlier work mostly focused on grass-trees competition in the vertical dimension. In this type of competition, it was assumed that deep tree roots use water not consumed by the shallow grass rooting system [7,8] and the competition for RWU becomes apparent when vertically-averaging the grass-tree rooting system [7,9]. Even within this restricted representation, resolving such rooting competition was shown to be essential in reproducing biomass dynamics [7,9]. One of the barriers to progressing on the root-water competition issue is the inherent three-dimensional nature of the problem. Here, a new 3D model of RWU is developed to investigate the effects of overlapping root-systems within a forest canopy so as to infer up-scaled representation of such competition effects on bulk ecohydrologic models.

RWU modeling: Modeling RWU requires coupling plant transpiration and photosynthesis together with a three-dimensional evolving soil moisture field. Two main approaches, both based on Richards' equation to describe soil water dynamics [2], have been used to model RWU: (1) a macroscopic approach and (2) a

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microscopic approach that accounts for the detailed root architecture. The first approach accounts for RWU by introducing a "macroscopic" sink term, generally defined as a function of spatially-distributed root parameters (e.g., root length density). This approach assumes that the vertically integrated RWU can be represented via a potential transpiration dictated by atmospheric demand for water vapor modulated by an ad hoc water stress function (e.g., Feddes approach [10]). Some compensatory mechanisms have been incorporated within such a framework [11,12]. When water potential gradients (WPG) are employed, this approach can reproduce important processes such as hydraulic redistribution (HR) [13]. HR has been observed in a number of experiments [14,15] and included in different modeling approaches [13,16–22]. While most models in this class can satisfactorily reproduce both compensation and redistribution mechanisms, they generally use a vertically distributed RWU approximation, thereby censoring any horizontal interactions among plants. Multidimensional macroscopic models do exist [12,23], but they generally use simplified RWU functions that may be unrealistic in heterogeneous soils [24]. The importance of a three-dimensional perspective has been recently underlined [25] spawning a number of simulations of water flow through soil and roots using a root hydraulic network [2,25–27]. This second approach includes detailed plant-scale models based on explicitly resolved root architecture coupled with the three-dimensional Richards equation for water flow in the soil-root system of an isolated single small plant or seedling [2,25,26]. Because the precise root architecture for multiple interacting trees is rarely known a priori, and given the computational burden involved, a root architecture approach is not yet feasible for large scale hydrological simulations. An intermediate approach that retains the 3D properties of the problem and yet provides a numerically-viable simplified RWU approach is needed when exploring the interplay of hydrological, physiological, and ecological mechanisms at the watershed scale. Existing 3D models (belonging to both categories) commonly neglect photosynthetic processes, which largely controls transpiration, and hence RWU. An approach that also accommodates these mechanisms and can be embedded in a robust three-dimensional soil moisture model offers a decisive advantage when generalizing plant-water relations at larger scales. With such a representation, the competition between plants for soil water (e.g., neighboring trees in a forest stand) can be made explicit and its effects on upscaled watershed processes can be explored.

Objectives: The main objective here is to develop a mechanistic 3D model of RWU so as to explore the implications of root competition on ecosystem transpiration and carbon uptake. More specific objectives are to (1) develop and apply a soil–plant-atmosphere model incorporating a 3D description of soil water dynamics, (2) investigate the effects of some biotic and abiotic compensatory mechanisms such as HR and Darcian redistribution on RWU and water use efficiency, and (3) evaluate the effects of tree-to-tree overlapping root zones on ecosystem level RWU rates. The main novelty is a framework in which a 3D hydrological model is coupled to plant transpiration and leaf photosynthesis that is then used to explore root water uptake for overlapping tree rooting systems in the presence of dynamic groundwater fluctuations.

2. Mathematical model

The transpiration flux is expressed in terms of gradients in water potential through a series of conductances along the pathway connecting water from the soil (ψ_i), to the xylem (ψ_R), and to the leaf (ψ_L) (Fig. 1). Stomatal conductance is assumed to maximize carbon gain, while minimizing water loss. The following assumptions are made [22]:

(a1) water extracted by roots only feeds transpiration and no water storage occurs within the plant system,
(a2) each soil layer is directly linked to the xylem through the root biomass allocated to the same layer,
(a3) energy losses in the root system are negligible compared to the dissipation in the soil and soil-root interface,
(a4) RWU is not limited by any other mechanism (e.g., nutrient limitation),
(a5) root growth is here ignored, though it may be significant at long time scales.

2.1. Soil–plant exchanges

A recent 1D root model [22] is expanded here to a 3D general framework. Richards' equation is used to describe soil moisture dynamics in a three-dimensional porous medium and is given as:

$$S_s S_w(\psi)\frac{\partial \psi}{\partial t} + n\frac{\partial S_w(\psi)}{\partial t} = \vec{\nabla}\cdot\left[\mathbf{K}_s K_r(\psi)\left(\vec{\nabla}\psi + \eta_z\right)\right] + q(\psi, x, y, z, t, \psi_L), \quad (1)$$

where S_s is the elastic storage term (m^{-1}), S_w is water saturation (–), ψ is the soil water potential (m), t is time (s), n is the porosity (–), $\mathbf{K}_s$ is the saturated hydraulic conductivity ($\mathrm{m\,s}^{-1}$) tensor, K_r is the relative hydraulic conductivity (–), $\eta_z = (0,0,1)^T$ is the gravitational potential energy gradient with z, the vertical coordinate, directed upward and $q(\psi, x, y, z, t, \psi_L)$ is a macroscopic source/sink term (s^{-1}) through which soil water dynamics is coupled with the root–plant system via the leaf water potential ψ_L. Anisotropic saturated hydraulic conductivity is modeled as a diagonal matrix with diagonal elements K_x, K_y, and K_z, the saturated hydraulic conductivities along the coordinate directions. Eq. (1) is highly nonlinear due to the functional dependence upon pressure head of the soil water retention curves, which are modeled following van Genuchten and Nielsen [28]. The numerical solution to Eq. (1) is obtained by means of a Finite Element approach with linear (P1) basis functions and implicit Euler time-stepping, as implemented in the CATHY model [29]. The scheme considers nonlinear boundary conditions at the soil surface to account for ponding or evaporation limitations due to variable surface soil moisture. The numerical solver is based on an unstructured tetrahedral grid and employs time step adaptation to ensure convergence for highly nonlinear problems and address the ODE stiffness resulting from the discretization of the nonlinear source term. Inexact Krylov-based Picard iteration with ad hoc efficient preconditioning is used in the solution of the nonlinear system of equations [30–32]. Discretization of the source term is obtained by means of the second order accurate midpoint rule, by which at each grid node i the source term $q_i = q(\psi_i, x_i, y_i, z_i, t, \psi_L)$ is multiplied by the corresponding nodal soil volume V_i. Coupling between the soil and the root system proceeds as follows: Single plants are defined by a surface grid node, j (with j between 1 and the number of plants in the model domain), which can be identified as the base of the plant trunk. The total water uptake per unit soil volume from node i, appearing in Eq. (1), is expressed as the uptake from all plants having non-zero root biomass at node i, i.e., $q_i = \sum_j q_{i,j}$. The term $q_{i,j}$ is the soil water uptaken (per unit soil volume) by the roots of plant j at grid node i. A plant node j is connected to each soil node within its root zone through a conductance, $g_{i,j}$, representing the path traveled by water from the soil pores into the nearest root within the finite element centered in i. The conductance $g_{i,j}$ expresses the water flux from the soil to the root (or viceversa) crossing the root membrane per unit area of the membrane and per unit difference of the total water potential between the soil and the root (see inset in Fig. 1). To obtain the flux per unit soil volume of the domain entering (or exiting) the root system at node i, it is necessary to account for the total root surface area per unit soil volume,