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A dynamic root simulation model in response to soil moisture heterogeneity

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Highlights

- A novel algorithm (space colonization) is used to calculate root hydrotropism.
- A model is proposed to couple interaction between root growth and soil–water flow.
- We compare effects of hydrotropism to water extraction and root length fraction.
- The model can be used to analyze water extraction process and root architecture.
- Based on grid, proposed method is flexible to couple with other soil processes.

Abstract

A three-dimensional dynamic model which is combined with root-system development and water extraction is proposed to simulate the interaction between root growth and soil–water flow. Hydrotropism is considered as one controlling factor of root growth in the model. In the paper, the dynamic root model is simulated based on L-systems. The space colonization algorithm is employed to compute hydrotropism caused by soil moist gradient. The soil–water flow, caused by water extraction rather than by evaporation and irrigation, is solved by finite-element method. A root simulation study is presented for water uptake by a maize root system. Effects of hydrotropism on root are demonstrated. The results show that the proposed method can couple root development to surroundings and analyze effects of hydrotropism to water uptake and root length fraction. Based on grid technology, the proposed method can provide a flexible root model which can be easily coupled with soil processes.

Keywords: L-systems; Hydrotropism; Space colonization; Water extraction; Root simulation

1. Introduction

Root architecture is important for plant to access soil resources. There are considerable evidences linking root architecture with water and nutrient acquisition efficiency. Because growth of root is very complex and plastic and it

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is very difficult to observe and quantify actual root architecture, studies of root are very challenging [10,30]. Modeling of root system development is therefore very useful for understanding the interaction between root systems and soil.

As reviewed by [7,33], some of root models relied on a fractal description that is defined as static fractal branching which was based on fractal properties of root parameters. Those models used statistical relationships between typical dimensions observed locally throughout the root systems. For example, FracRoot was created to describe root system of tree based on the theory [28]. Other models were based on the developmental rules of root apices and incorporated soil effects on root growth. By formalizing and combining the main dynamics developmental rules of root architecture into a mathematical frame, dynamic 3D root developmental models were defined. There were some classical models based on the theory, such as ROOTMAP [5], Root type [23], SimROOT [21], SPACSYS [39] and with substantial improvement and extensive researches [8]. Furthermore, functional–structural plant models (FSPM) broadly used in plant modeling were used to model root architecture based on feedbacks between functions and structures of root [37]. For example, L-systems had been used for root architecture modeling and visualization [17,20]. GreenLab which was another FSPM framework had been applied to root modeling and performing [40]. Based on those theories, root models coupling with interaction between the root and soil such as water and nutrient uptake were proposed to simulate growth of root. Fitter et al. developed a root model to analyze the exploration efficiency of root systems in dependence of root architecture [11]. Clausnitzer et al. developed a root growth model and analyzed water flow in the soil root zone [3]. Then the model was further extended by Somma et al. for nutrient uptake [31]. Tsutsumi et al. simulated hydrotropism using the difference in elongation rates in elongation points of root in soil moisture gradient [34]. Dunbabin et al. analyzed the effects of different root system architectures on nitrate uptake efficiency and subsequently predicted water and nutrient uptake by integrating RootMap into a simulated environment [6]. Roose and Fowler derived sink terms for nutrient and water uptake from a continuous root system growth model which could be solved analytically [26]. Walk et al. used SimRoot to assess the effects of trade-off of different root systems on phosphorus acquisition [38]. Javaux et al. described water flow between the soil and root domain [16]. Leitner et al. presented a modular approach for root growth, root architecture and root–soil interactions based on L-systems, taking tropisms and nutrient uptake into account [17]. Ireson and Butler summarized root system development models in response to soil–water status [15]. Dunbabin et al. provided an overview of the development of three-dimensional root architectural models which were used to investigate numerous root–soil interactions over a range of spatial scales [7]. Chen et al. proposed a simulation modeling to predict and identify phenotypic plasticity, root growth responses and phosphorus use efficiency [2]. Henke et al. presented a systematic comparison of the effects of mechanisms of chemotropism, spacing of lateral root and hierarchy between laterals and their mother root on the whole root plasticity when the root is grown under four distinct nutrient distribution scenarios using a functional–structural root model [22]. Lobet et al. presented a new model, Planet-Maize, with the purpose of investigating the effect of environmental and endogenous factors on the growth and water relations of the maize plant [12].

Above all, a major challenge of root modeling is the dynamic interactions of soil properties and root growth. Because root surroundings are heterogeneous in both space and time and plants cannot move to more suitable environments, root has to modify growth and development (plasticity) to suit environmental condition when unconformable environment occurs. For example, Some experimental results showed that root growth could be influenced under soil moisture gradient [1,9]. Also some valuable work had been done to model effects of hydrotropism on growth of root [17,35,36].

Hydrotropism is that root elongation bends toward a source of moisture according to soil–water gradient. According to Tsutsumi [35], root hydrotropism is an irreplaceable factor for representing the effects of soil–water flow on root system development. The objective of this study is to propose a dynamic model for root growth, root architecture and root–soil interactions. We use it to analyze root development and soil–water extraction by considering the effects of hydrotropism. In the present model, we apply three-dimensional Richards' equation to calculate water flow in unsaturated soil. The water extraction by root system can be calculated by adding a term of water-extraction intensity to the equation. In order to consider hydrotropism, we subdivide root region into grid or voxel. Then hydrotropic direction is calculated by space colonization algorithm under soil moist gradient. New root growth direction is computed by taking into account the initial growth direction, hydrotropism and other tropisms (gravitropism defined as downwards growth movement by root in response to gravity, plagiotropism defined as aligned growth movement at some angle to the direction of stimulus e.g.). In this study, the dynamic root model is based on L-systems. The main goal of this paper is to analyze root hydrotropism calculated by space colonization algorithm rather than root