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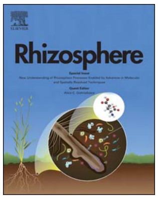

What can we learn from in-soil imaging of a live plant: X-ray Computed Tomography and 3D numerical simulation of root-soil system

Xiaofan Yang[a,*], Tamas Varga[a,b], Chongxuan Liu[a,c], Timothy D. Scheibe[a,b]

[a] *Pacific Northwest National Laboratory, P.O. Box 999, Richland, WA 99354, USA*
[b] *Environmental Molecular Sciences Laboratory, P.O. Box 999, Richland, WA 99354, USA*
[c] *School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, Guangzhou 518055, China*

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ABSTRACT

Plant roots play a critical role in plant-soil-microbe interactions that occur in the rhizosphere. X-ray Computed Tomography (XCT) has been proven to be an effective tool for non-invasive root imaging and analysis. A combination of XCT, open-source software, and in-house developed code was used to non-invasively image a prairie dropseed (Sporobolus heterolepis) specimen, segment the root data to obtain a 3D image of the root structure, and extract quantitative information from the 3D data, respectively. Based on the explicitly-resolved root structure, pore-scale computational fluid dynamics (CFD) simulations were applied to numerically investigate the root-soil-groundwater system. The plant root conductivity, soil hydraulic conductivity and transpiration rate were shown to control the groundwater distribution. The coupled imaging-modeling approach demonstrates a realistic platform to investigate rhizosphere flow processes and would be feasible to provide useful information linked to upscaled models.

Root water uptake (driven by transpiration caused by the water potential gradient between the atmosphere and plant) is one of the most important processes in subsurface flow and transport modeling (Carminati, 2012), which motivates new research aimed at understanding roots and their functioning (Šimůnek and Hopmans, 2009). However, mechanisms in root water uptake are poorly studied and largely ignored in macro-scale models due to the following difficulties in both imaging and modeling: 1) explicit imaging and image processing are difficult caused by the complexity of the root architecture and soil variability; 2) estimation of plant root and soil properties and associated model parameters is difficult; 3) coupled hydrologic-biological processes involved in root uptake are poorly understood hence difficult to be modeled. Recently, integrated high-resolution imaging and pore-scale modeling approaches have become a powerful tool to study root-soil-groundwater interactions (Javaux et al., 2008, 2013; Schroder et al., 2013; Keyes et al., 2013). Reviews of root models and rhizosphere can be found in Neumann and Cardon (2012), Dunbabin et al. (2013), Vereecken et al. (2016), Roose et al. (2016) and on The International Soil Modeling Consortium website (https://soil-modeling.org/governance).

Recently non-invasive XCT imaging techniques were utilized with a suite of open-source and in-house developed codes to distinguish and reconstruct plant roots of a living plant grown in a pot from the surrounding soils at micron-scale resolution (Suresh et al., 2016). A multiscale groundwater model developed by Yang et al. (2014, 2015) has the ability to specify heterogeneous properties for both soil and root segments and allows the explicit modeling of the spatiotemporal variations of root water uptake. It extends the Stokes-Brinkman equation by adding a Darcy term to the classic Navier-Stokes equation. It then links to water retention function and mass conservation equations to formulate a single system of equations describing fluid flow in mixed media (e.g. the root-soil system) under both saturated and unsaturated conditions. By combining the imaging and modeling capabilities, the current short communication serves as a pioneer study of investigating the role of plant roots and will provide a platform to conduct future research (e.g. nutrient uptake, hydraulic redistribution, etc.). The objectives of the paper include: 1) addressing the challenges in root imaging and modeling and 2) utilizing the imaging-modeling approach to study the root water uptake. In the following sections, the integrated approach and methods will be introduced followed by the results from the root water uptake simulations.

X-ray Computed Tomography (XCT) scanning of the root specimen was performed using an X-Tek/Metris XTH 320/225 kV system (Nikon Metrology, Fig. 1a). The data were collected at 85 kV and 190 A X-ray power with 1 s exposure time to maximize color contrast in the data while keeping the noise minimal. A Prairie dropseed (Sporobolus

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[*] Corresponding author.
E-mail address: xiaofan.yang@pnnl.gov (X. Yang).

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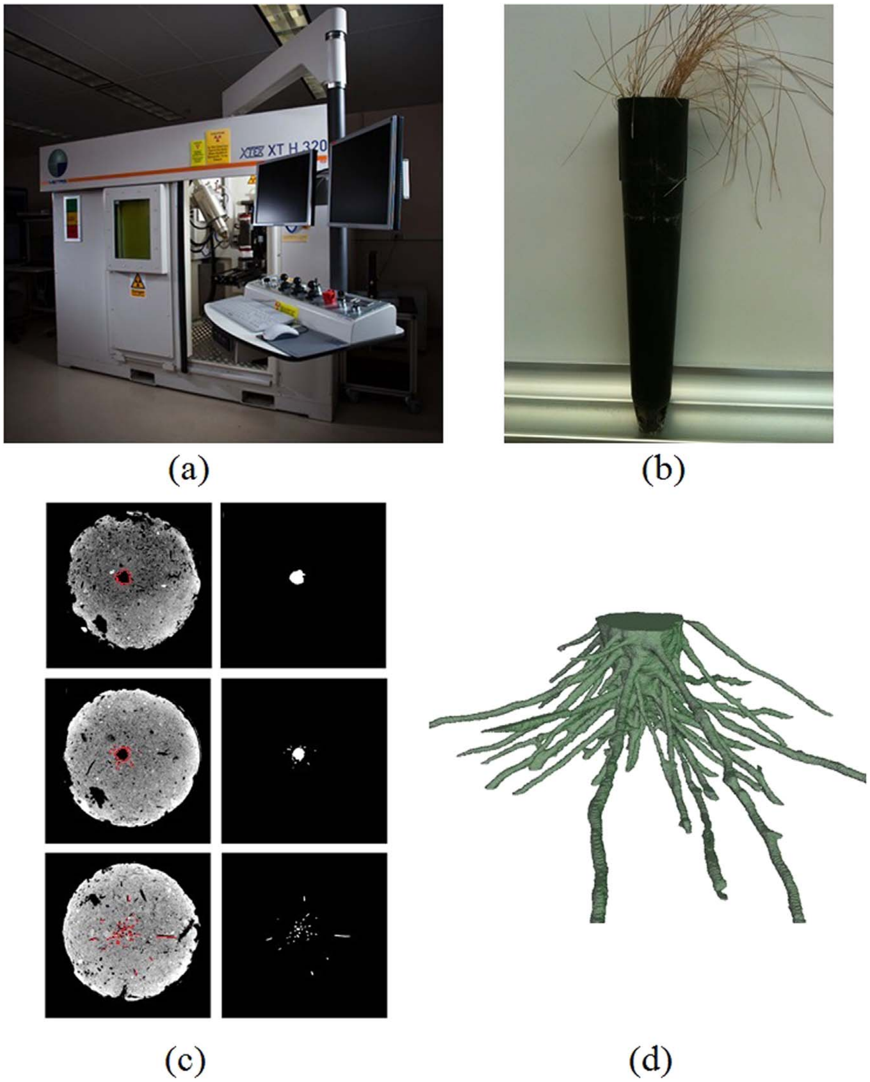

Fig. 1. (a) Picture of the scanner XTEK XT H 320/225 (Nikon); (b) Grass sample in its pot used for imaging; (c) Segmentation by RooTrak: Representative pairs of slice images showing segmentation by RooTrak – top, mid region, bottom region slice with corresponding slice of the segmented root (modified from Suresh et al. (2016)); (d) Image of the reconstructed root.

heterolepis) was sampled from the field and selected as the specimen (living plant in a pot, Fig. 1b). Details of the specimen and the associated living conditions can be found in Suresh et al. (2016). The sample was rotated continuously during the scan with momentary stops to collect each projection (shuttling mode) to minimize ring artifacts. 3142 projections were collected over 360° with 1 s exposure time and 4 frames per projection. Image voxel size was 31 µm × 31 µm × 31 µm.

The raw images were reconstructed to create a three-dimensional dataset using the software CT Pro 3D (Metris XT 2.2, Nikon Metrology, UK), producing a volume file approximately 1500 × 1500 × 1000 voxels in dimension. The reconstructed volume file was used to create a stack of images of a selected orientation (top view, Fig. 1c) using the open-source image-processing program ImageJ 1.6 (http://imagej.nih.gov/ij/). The image stack was then segmented through the open-source RooTrak software (Mairhofer et al., 2012, 2013) to segregate the root (marked in red in Fig. 1c) from the surrounding soil as well as any other roots from different plants around it. Finally, the volumetric stack containing only the root network was produced (Fig. 1d), which was then used to create the final images/animation in Volume Graphics Studio Max 2.1 (Volume Graphics Studio, Heidelberg, Germany). Quantitative information, such as root volume and surface area could be extracted from the 3D data using an in-house developed code ImeshJ. More details of the XCT, segmentation and data reconstruction can be found in Suresh et al. (2016).

The pore-scale numerical model for the current root-soil system solves a modified form of the classic Navier-Stokes (N-S) equation with a Darcy term added to the right-hand-side of the momentum equations (Eq. 3.1). The continuity equation under both saturated and unsaturated conditions is generally described as shown in Eq. (3.2) (Yeh, 1999).

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -g\nabla h + ve\nabla^{2}\mathbf{u} + \mathbf{g} - g\mathbf{K}^{-1}\cdot\mathbf{u} \tag{3.1}$$

$$F\frac{\partial h}{\partial t} = -\nabla\cdot\mathbf{u} + s \tag{3.2}$$

where $\mathbf{u}$ is the velocity vector, t is time, g is the gravitational constant, $\mathbf{g}$ is the gravitational force, h is the pressure head, v_e is the effective kinematic viscosity (defined as μ/ρ, where μ is the dynamic viscosity and ρ is the fluid density), F is the storage coefficient, $\mathbf{K}$ is the hydraulic conductivity tensor that defines the heterogeneity of the system and s is the source/sink term.

A previously-developed three-dimensional CFD code based on the finite-difference method was used to discretize (using the same resolution as in XCT for the structured mesh) and numerically solve the governing equations. The structured grid may introduce some artifacts since the root surface is not smooth, which requires further evaluation. However, a previous study on flow in a beads pack (Yang et al., 2013)