CAPTURING 3D WATER FLOWS IN ROOTED SOIL BY FAST NEUTRON TOMOGRAPHY

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Keywords: fast neutron tomography, in-situ, dynamic 3D water mapping, rhizosphere

Summary: Neutron tomography is an unique tool to visualize plant root systems and the distributions of water around roots *in situ*. Due to long acquisition times it was so far, however, not possible to observe dynamic changes in 3D. Employing a new exposure mode we boosted the acquisition speed achieving time resolutions of 10 s per tomogram. We succeeded to visualize the root water uptake and an ascending water front in the soil column in three dimensions.

1. INTRODUCTION

Non-invasive imaging techniques are the key for better understanding the root-soil interaction which is of great relevance for both plant and soil scientists. Neutron imaging has proven a powerful non-destructive technique to study the architecture of root systems and the water distribution in the surrounding soil *in situ* [1]. Due to its high temporal resolution (few seconds) neutron radiography (NR) is capable to capture dynamic changes in the local water distribution of the sample. Using D_2O as tracer substance NR has been successfully applied to visualize water transport phenomena in plants, e.g. root uptake (Zarebanadkouki *et al.*, 2012), axial transport in the xylem (Matsushima *et al.*, 2009) and the formation of embolisms (Tötzke *et al.*, 2013). These studies provided valuable insights into the root uptake and axial water transport in plants. The analysis of water flows were, however, intrinsically restricted by the two-dimensional imaging approach. Extending the observation to three dimensions promises a great leap forward in understanding the water flow into the roots. Insufficient time resolution has certainly been the greatest obstacle for visualizing three-dimensional flows by means of neutron tomography. The acquisition of a tomogram usually takes several hours. Drastic acceleration of the acquisition process is, therefore, necessary to resolve the water dynamics of the rhizosphere in three dimensions.

2. EXPERIMENTAL METHOD

We performed ultra-fast neutron tomography to visualize the water uptake by plant roots. Lupine plants (*lupinus albus*) were planted in sandy soil and grown under controlled conditions using glass cylinders (Ø 27 mm) as plant containers.
The experiments were carried out at the Helmholtz Center Berlin using the CONRAD II neutron imaging instrument (Kardjilov *et al.*, 2016, Helmholtz-Zentrum Berlin 2016). A detector system consisting of a 200 µm thick ^{6}LiZnS:Ag scintillator screen and sCMOS camera (Andor 'Neo') was employed at the middle measure position of the instrument where beam conditions are suitable for high speed and high resolution measurement, respectively. After binning (2 × 2 and 3 × 3) the effective pixel size was 110 and 165 µm, respectively. During the measurement the sample was mounted on a manipulation stage 4 cm in front of the scintillator. In contrast to the usual acquisition mode in which the sample is stepwise rotated over a range of 180° or 360° we rotated the sample at a constant speed while images were taken continuously. The speed of rotation was adjusted with respect to the exposure time such that 300 radiographic projections were taken over a range of 180°. Exposure time ranged between 0.2 s - 0.05 s resulting in total acquisition times between 60 s and 15s. By reducing the number of projections to 200 a further decrease of total acquisition times to 10 s was possible. During the experiments plants were watered from the bottom with D_2O. The ascending water front and subsequent root uptake were measured tomographically.

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3. RESULTS

Figure 1 shows the root system of a lupine plant measured in a series of tomograms with increasing speed of acquisition (t = 60, 30, 15, 10 s). Note, that already the slowest acquisition time (t = 60s) represents a speed up by factor 100 with respect to standard neutron tomography. While further reducing the acquisition time by factor 6 (from left to right in fig. 1) the major information about the root system architecture could be greatly retained, i.e. shape and orientation of tap and laterals root are clearly visible. The boost of measure speed was possible because of the modified acquisition procedure and the high and constant neutron flux provided at the CONRAD II instrument. Quality and time resolution of these measurements render the observation 3D water flows possible.

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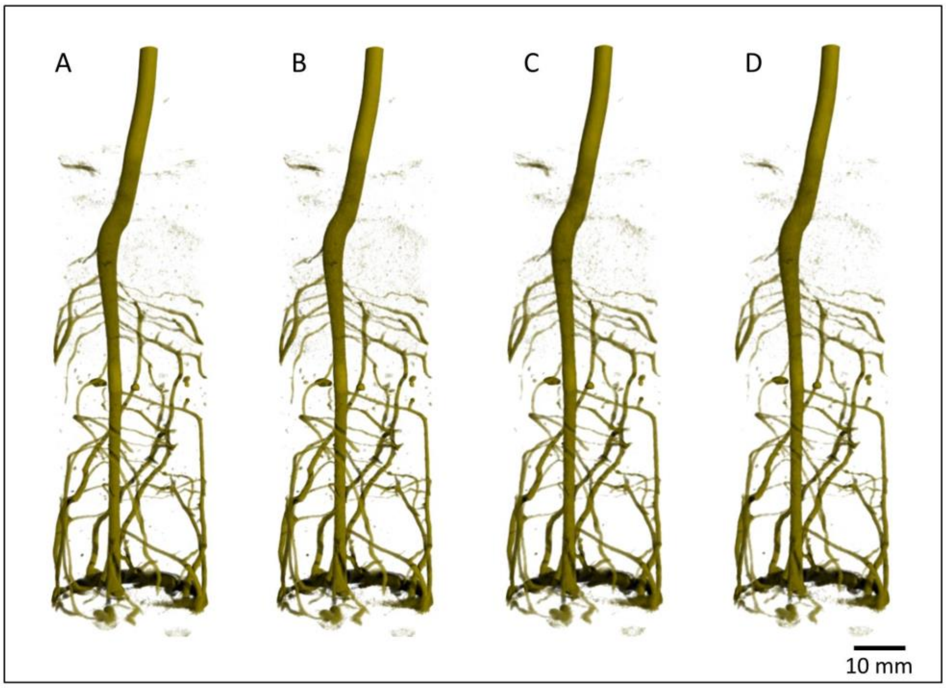

Figure 1: Lupine root system grown in sandy soil (total soil water content was 0.10 cm^3/cm^3) captured by neutron tomography at increasing measure speed. Total acquisition times were A) 60 s, B) 30 s, C) 15s D) 10 s. Even at highest measure speed the major features of the root system were retained.