The essential momentum of neutron imaging approaches to reveal water dynamics at the root-soil interface

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+

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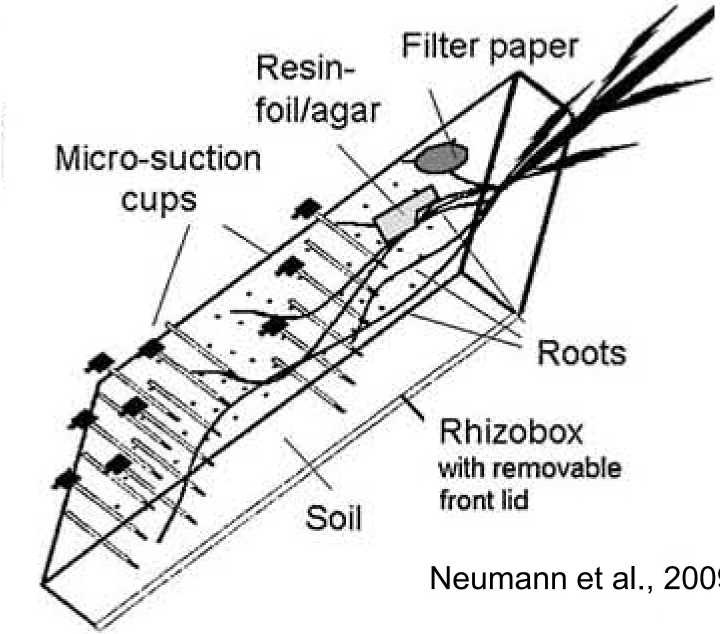
Conventional studies of soil water dynamics

Tensiometer & TDRs

Menon et al., *Plant & Soil*, 2005

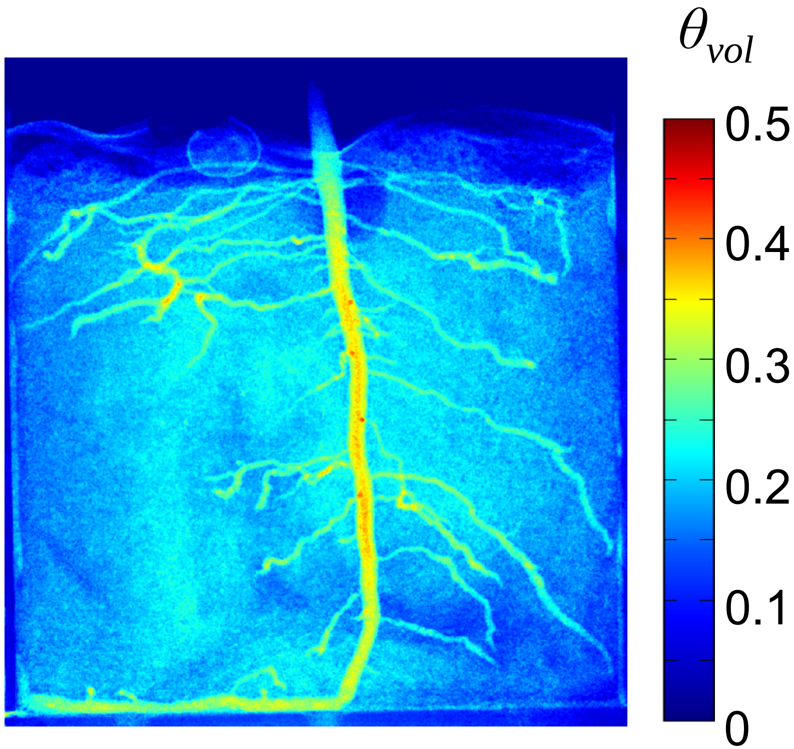
Laboratory columns & lysimeters



Rhizoboxes or the like

Neumann et al., 2009

The alternative – Non-invasive Imaging in small rhizobox and column set-ups



- Non-invasive, non-destructive
- Continuous measurements
- Not averaging over a larger local volume

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Neutron radiography facilities

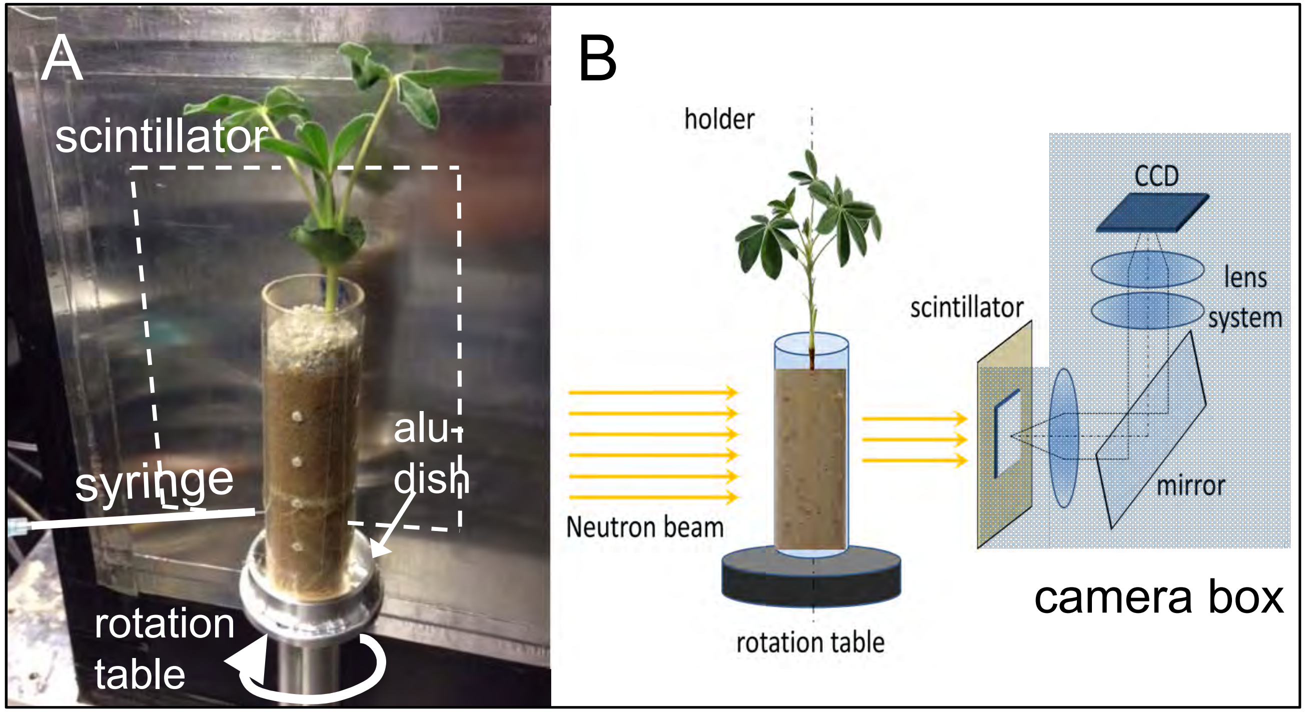
Facilities where we have done neutron imaging

⇒ Paul Scherrer Institut, Villigen, Switzerland

⇒ Helmholtz Centre Berlin, Germany

⇒ ILL & Universite Grenoble Alpes, France

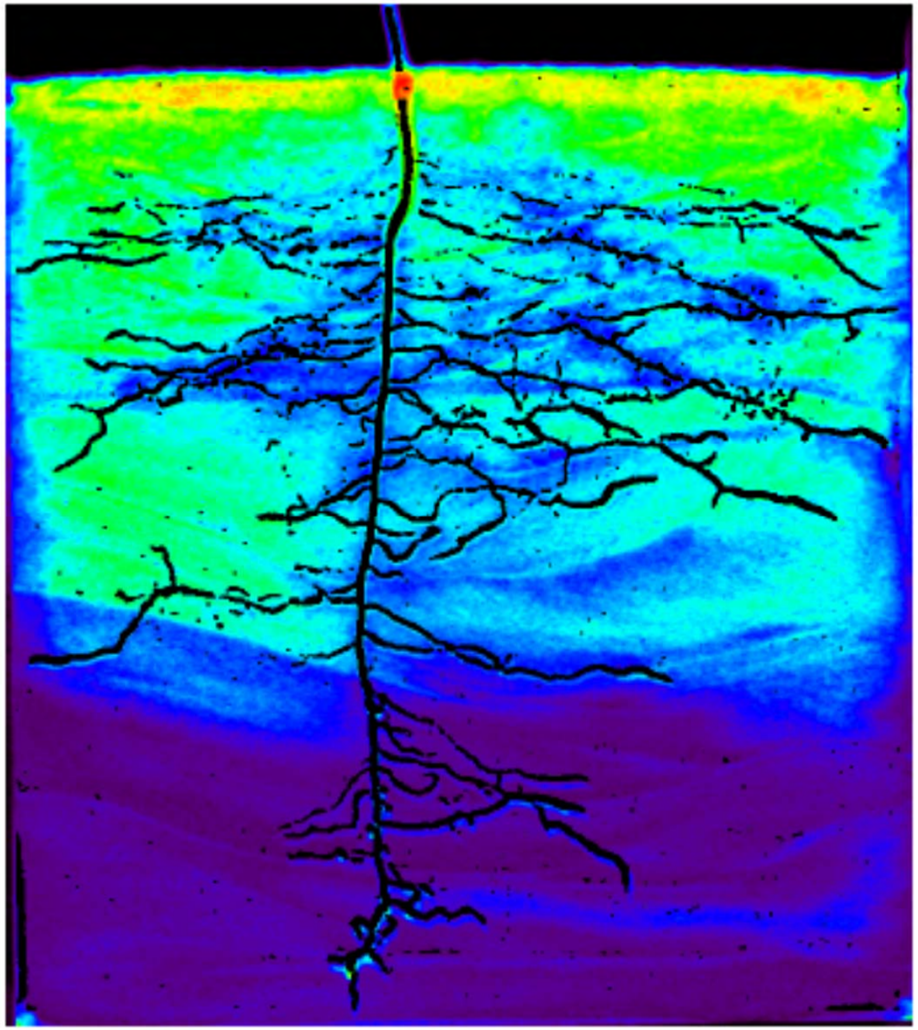
www.psi.ch



HZB, Berlin

Neutron radiography of a plant-soil system

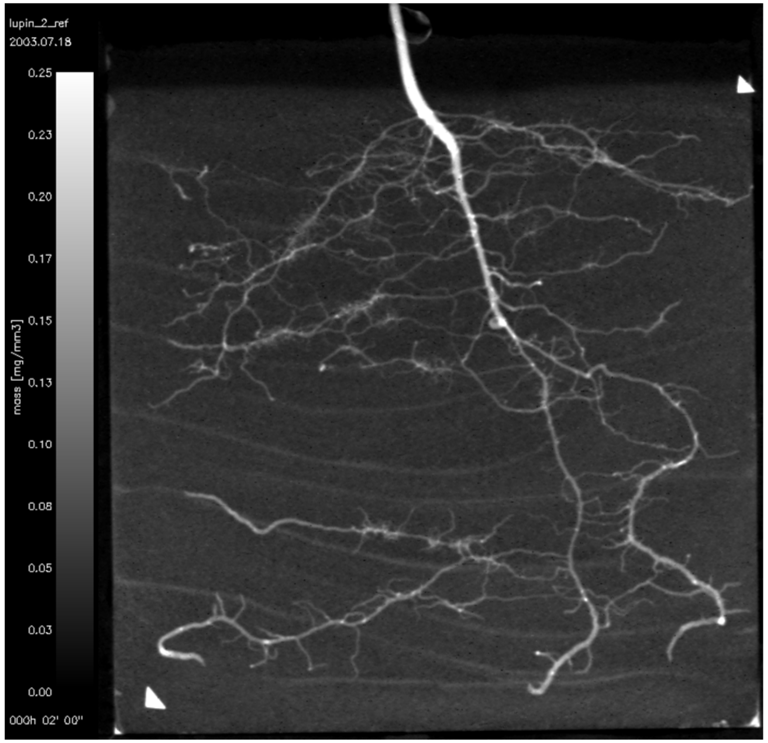
→ water content distribution and root structure



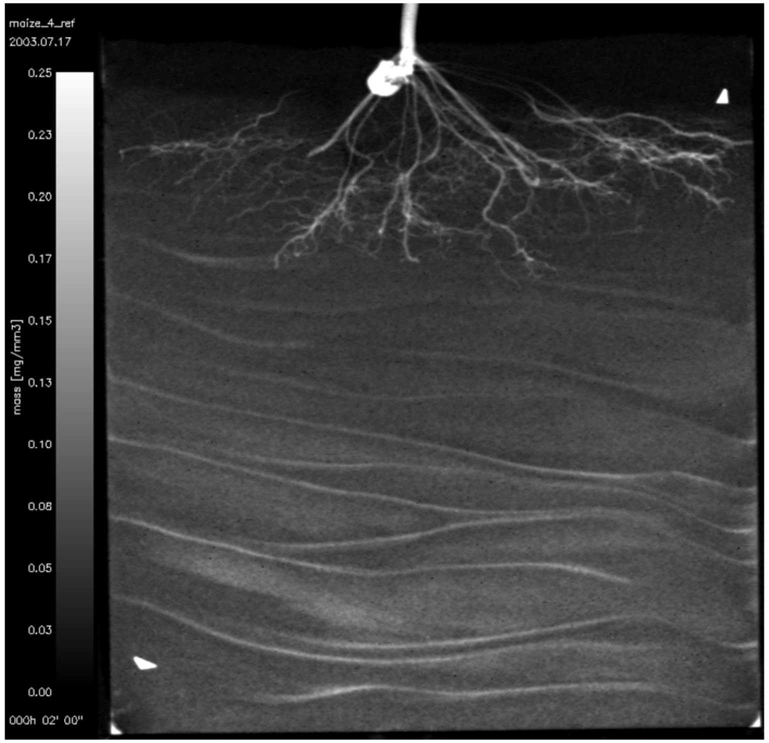
S. Oswald et al., Vadose Zone journal, 2008

Root growth:

lupine



corn



S. Oswald et al.,Vadose Zone journal, 2008

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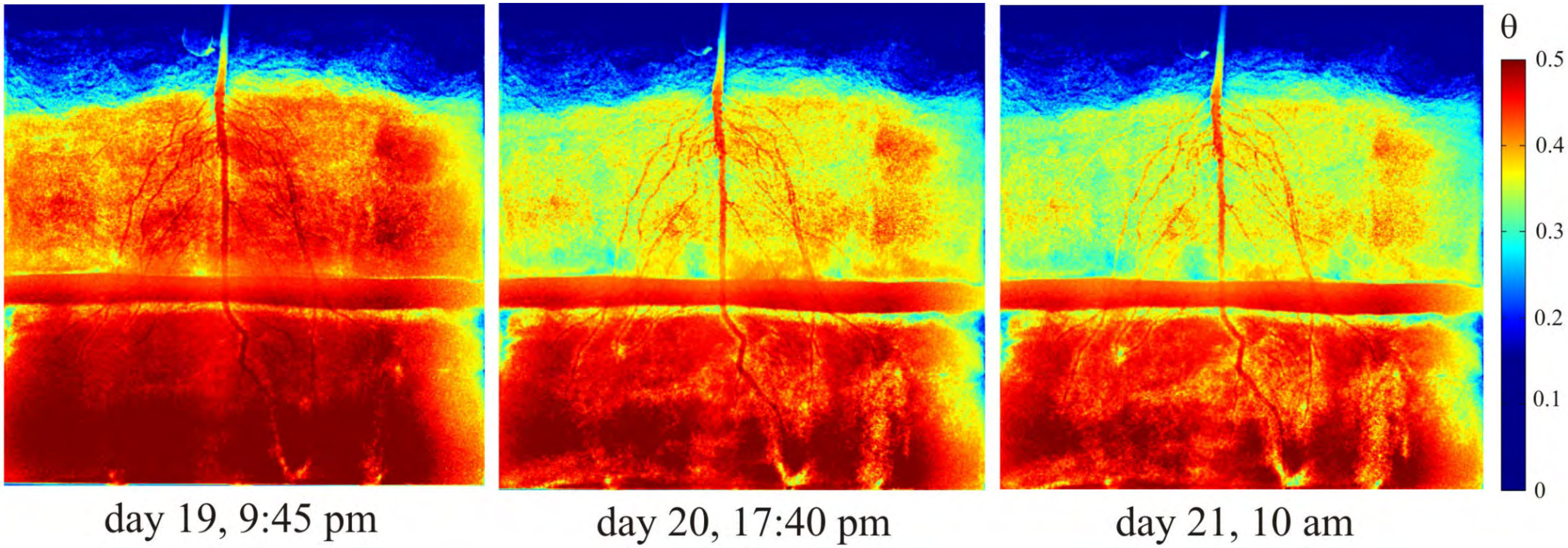
Hydraulic barriers for separation during infiltration and drying



N. Rudolph et al., of Soils and Sediments, 2012

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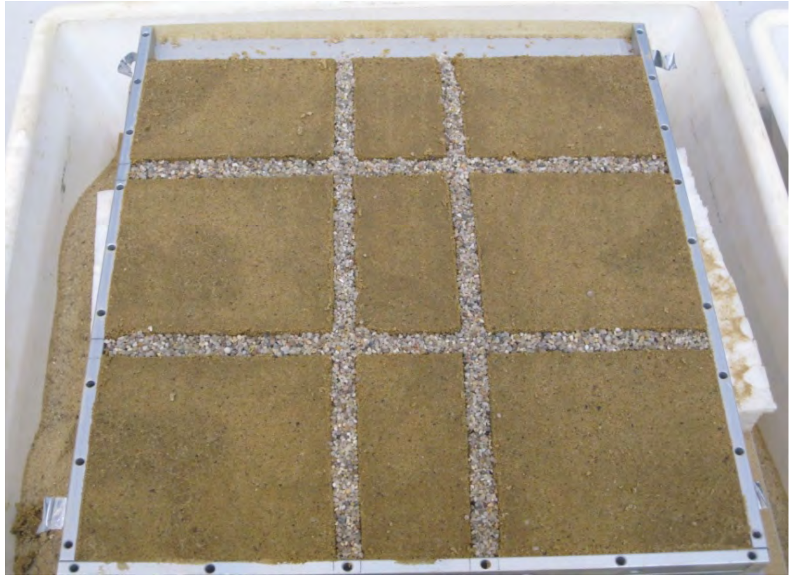
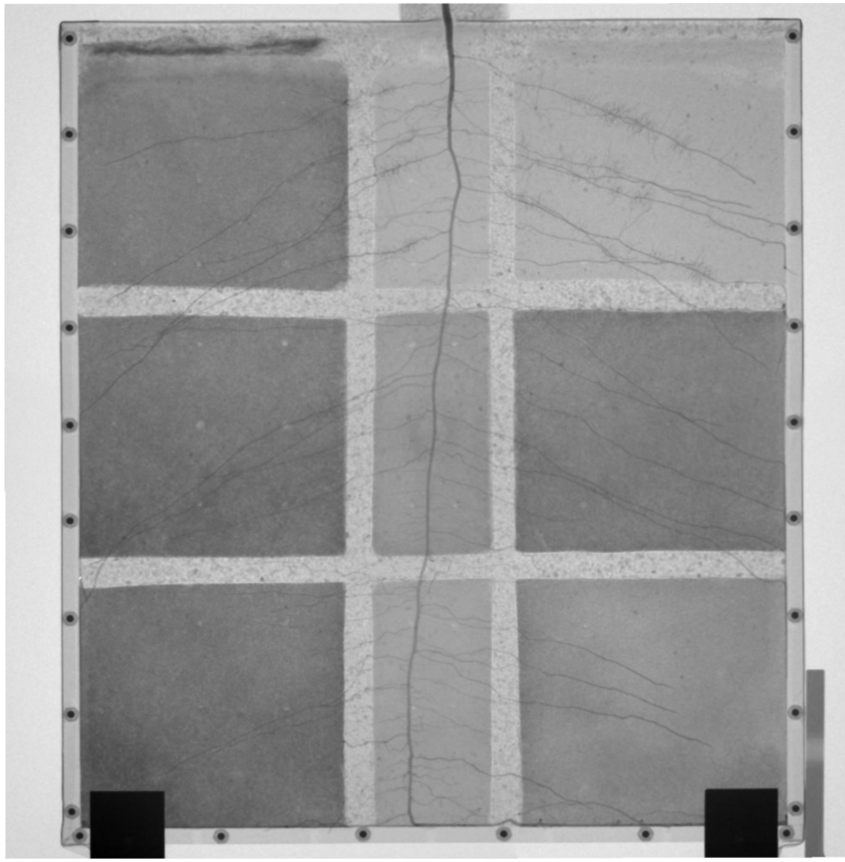
Experiment design for compartments of different water contents

30*25*1 cm³ Aluminum containers



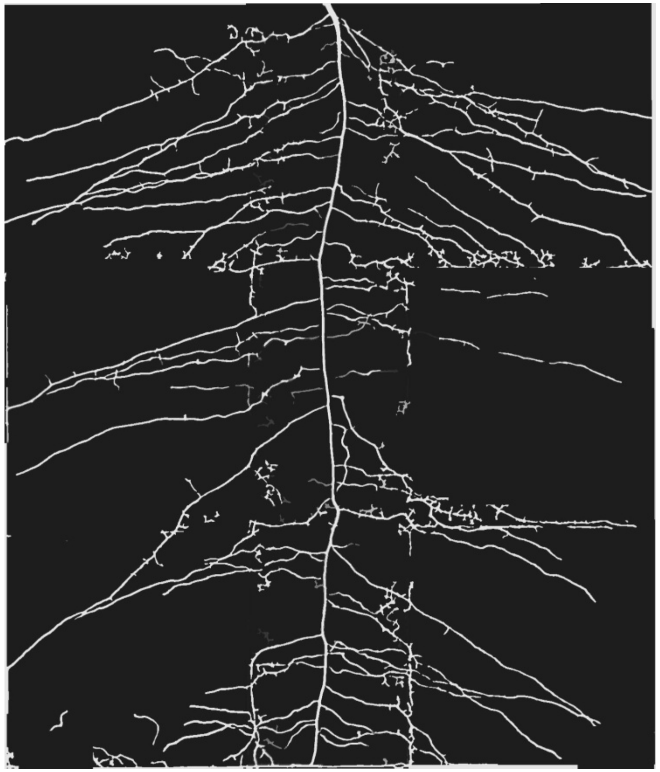


A. Dara et al., Plant & Soil, 2015

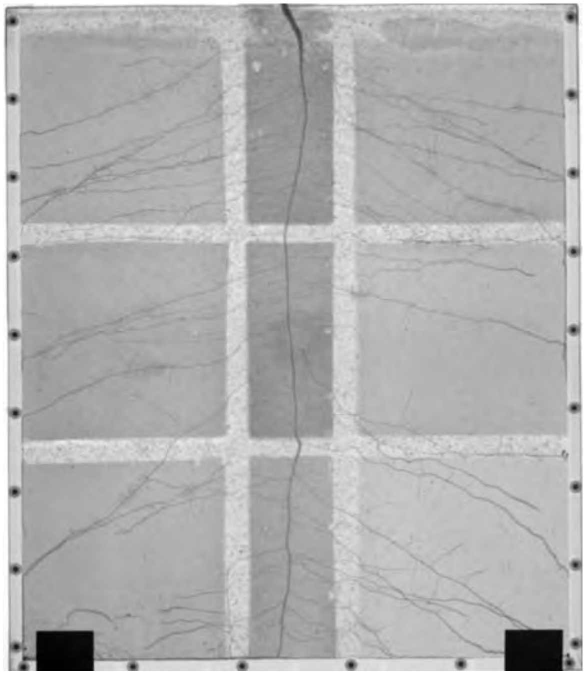
Image analyses to derive local water balance and uptake

A. Dara et al., Plant & Soil, 2015

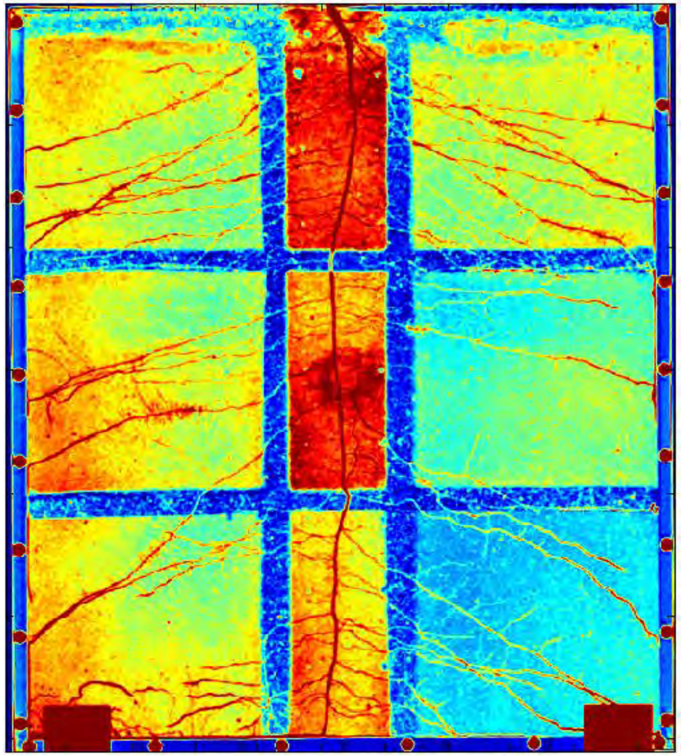
Root segmentation



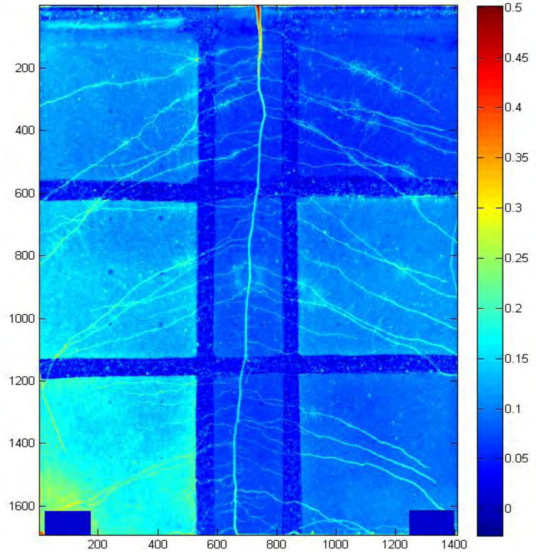
Raw Radiograph



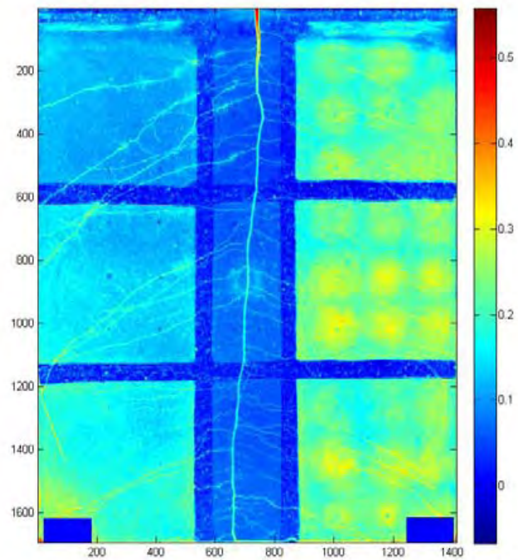
Water content quantification



Water balance in individual compartments

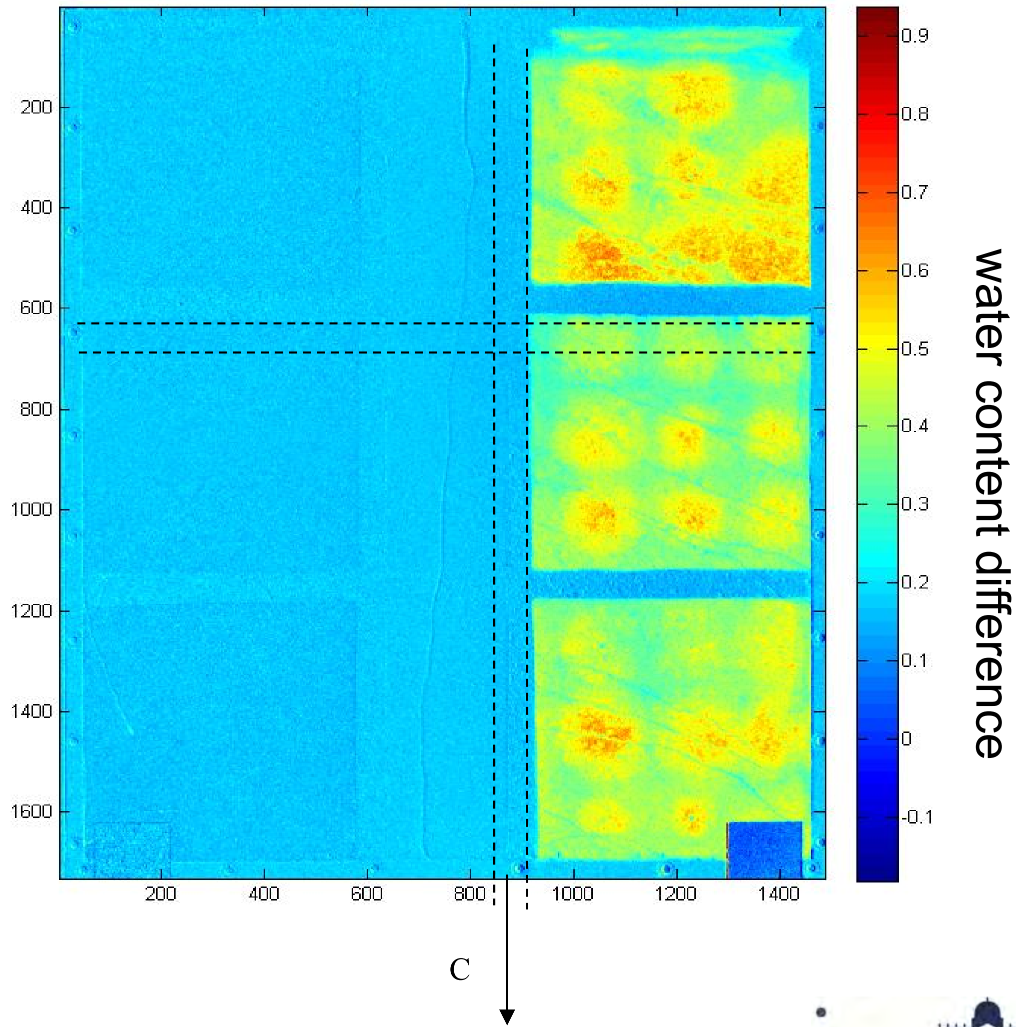


After drying, before watering



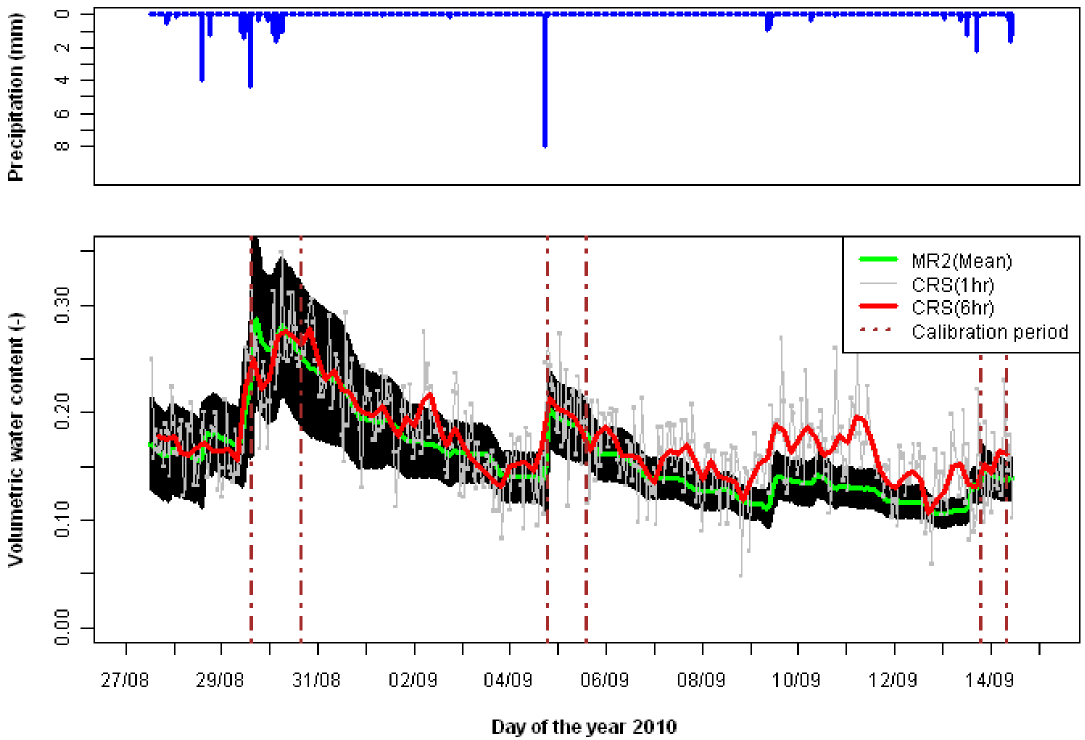
After injection on right side

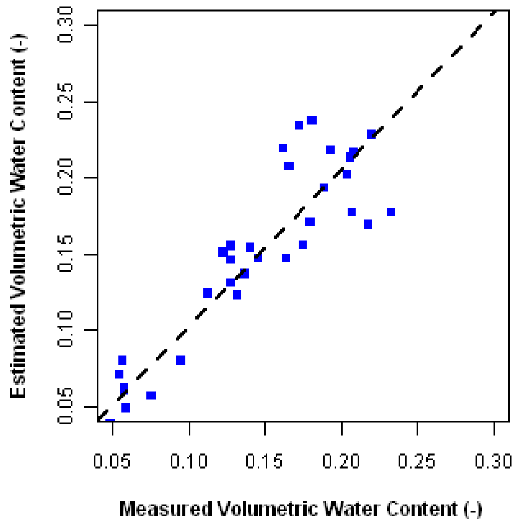
A. Dara et al., Plant & Soil, 2015



Coarse-sand layer (capillary barrier)

Neutron „imaging“ in the field via neutrons produced by cosmic-rays naturally?





C. Rivera Villarreyes et al., Hydrol. Earth Syst. Sci., 2011

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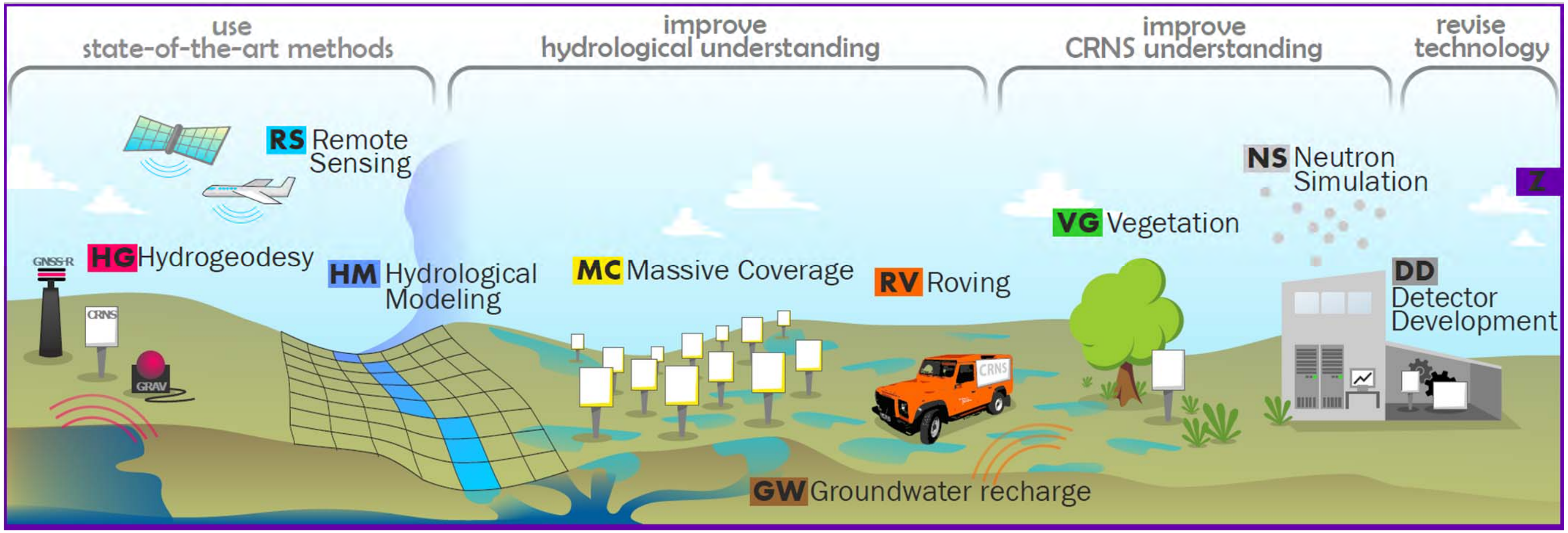
Soil moisture at field scale via neutrons!



Mapping soil moisture via cosmic-ray neutron sensing for the first time - current field monitoring campaign

DFG FOR-2694

Cosmic Sense

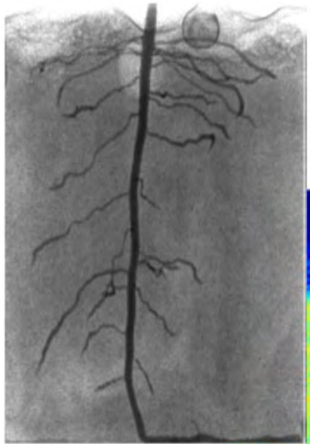
www.uni-potsdam.de/cosmicsense

Needs for NI laboratory plant-soil studies

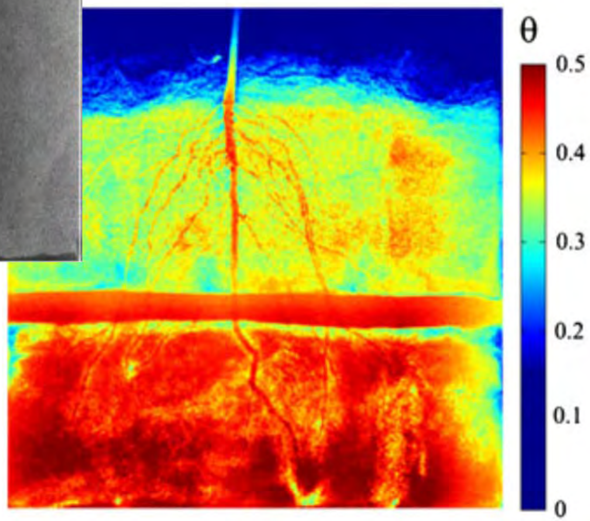
- Controlled environment for growth period and during experiments
- Large(r) samples
- Quicker tomographies with high resolution
- Combination with other imaging methods
  - direct at NI facility
  - same samples
  - similar resolution

2D vs. 3D imaging mode

Neutron radiography



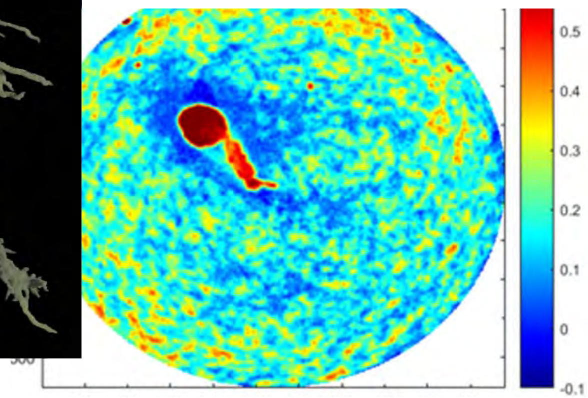
- Very good contrast for roots in soil



- 2D soil water mapping
- Dynamic measurements (tracer injection)

Neutron tomography

- 3D root architecture and development

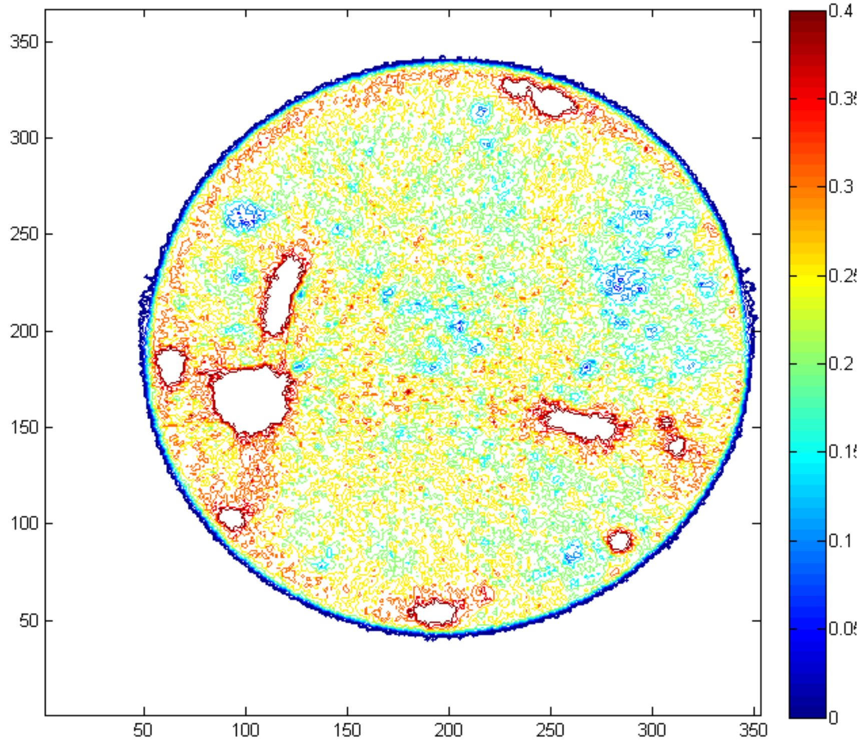


- 3D soil water maps
- No dynamic measurements – *until recently*

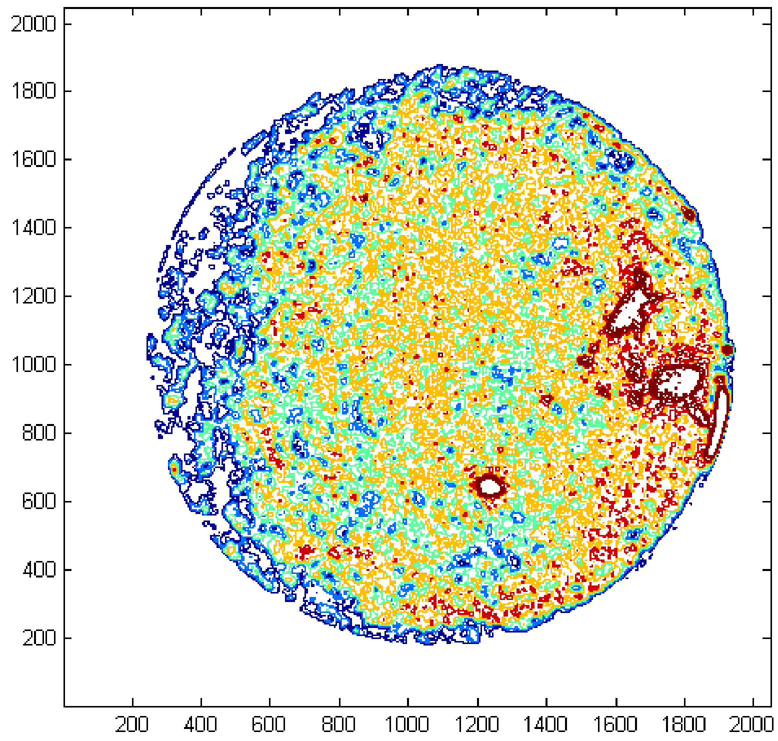
Rudolph et al. (2012), J Soils Sediments

Imaging the rhizosphere behavior in 3D: level 1

Chickpea



Maize



Root-microtomography in cylinder by neutron imaging

(A. Moradi et al., *New Phytologist*, 2011; showing mucilage effect)

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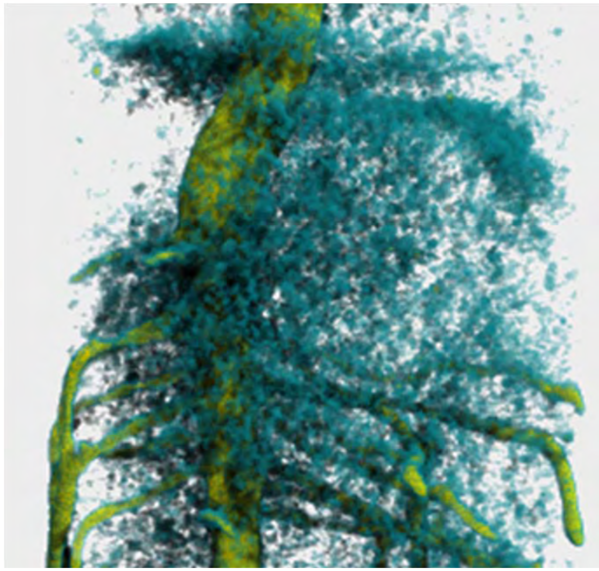
Imaging the rhizosphere behavior in 3D: level 2

Root system

→ NT/X-ray CT

Soil water



→ NT

Soil microstructure

→ X-ray CT

Combining X-ray CT and NT
→ More comprehensive picture of rhizosphere

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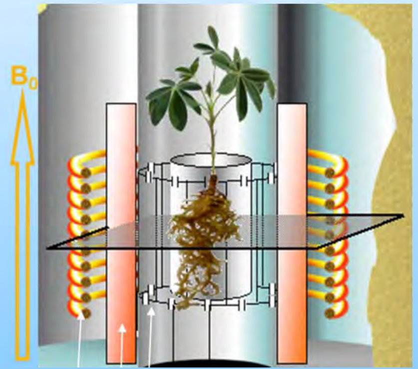
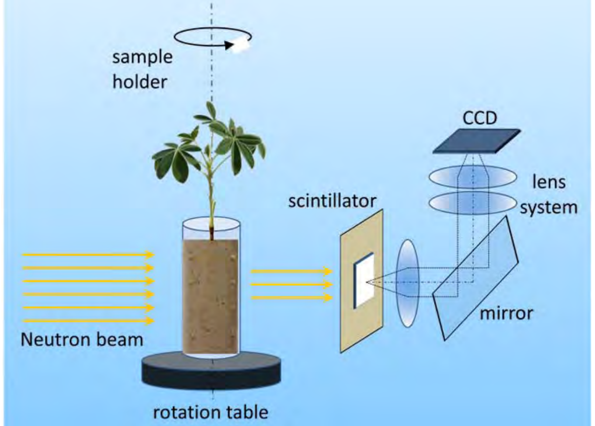
Imaging the rhizosphere behavior in 3D: level 3

Magnetic Resonance Imaging (MRI)



+ voxel signal = f (water, tracer, diffusion, flow, pore structure)
+ thick and wet samples
- relatively insensitive

Neutron Tomography (NT)

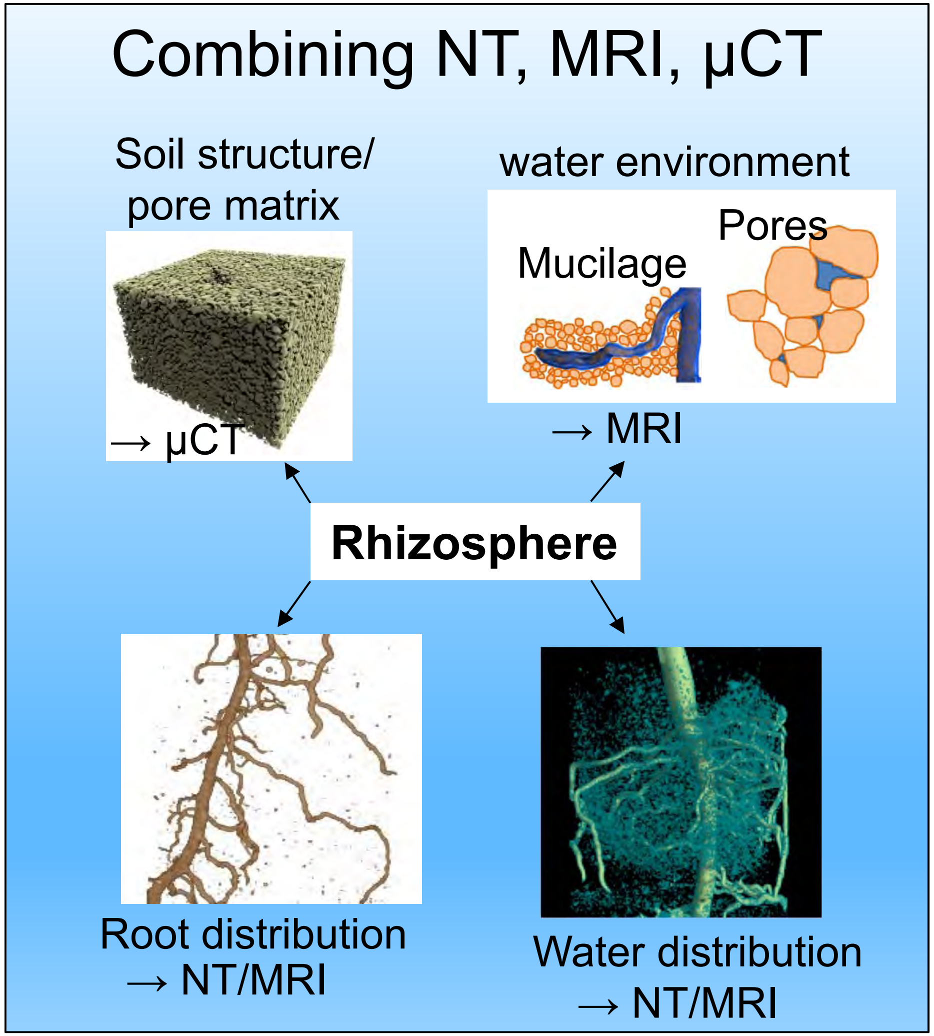


+ high resolution (0.05mm)
+ high sensitivy
+ 3D water distribution
- thin or dry samples

Microfocus X-ray CT (μCT)

+ high resolution (0.05mm)
+ 3D structure of soil matrix
- thin samples
- weak contrast for roots and water

Objectives of combined imaging



Comprehensive picture of rhizosphere

- Capturing the root system in the same hydro-physiological state

→ novel transportable MRI for direct combination of NI/MRI at the same plant sample

- Co-registration

→ transformation of different 3D data sets (different resolution, orientation) into a common coordinate system

Christian Tötzke et al., manuscript in preparation

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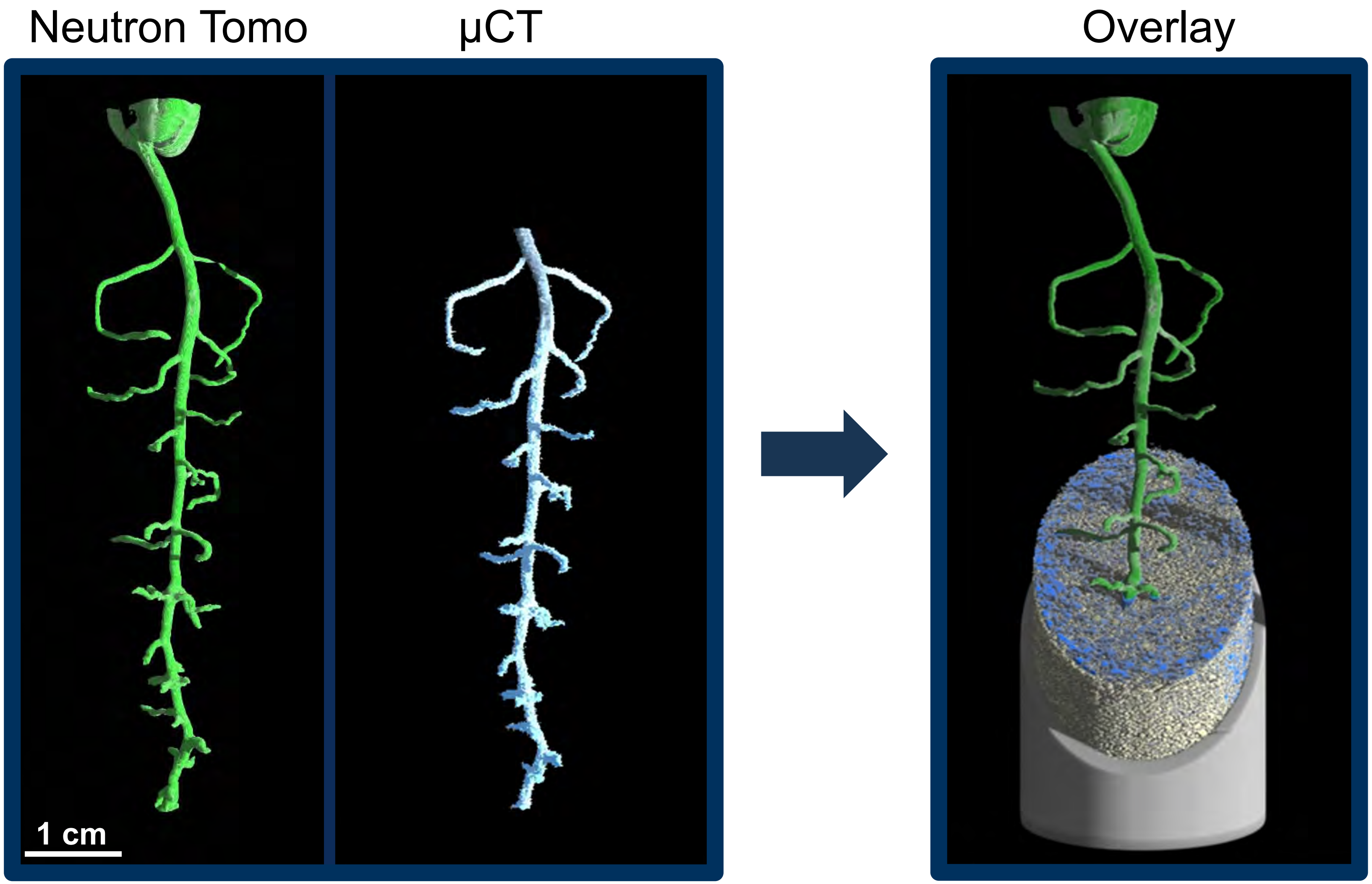
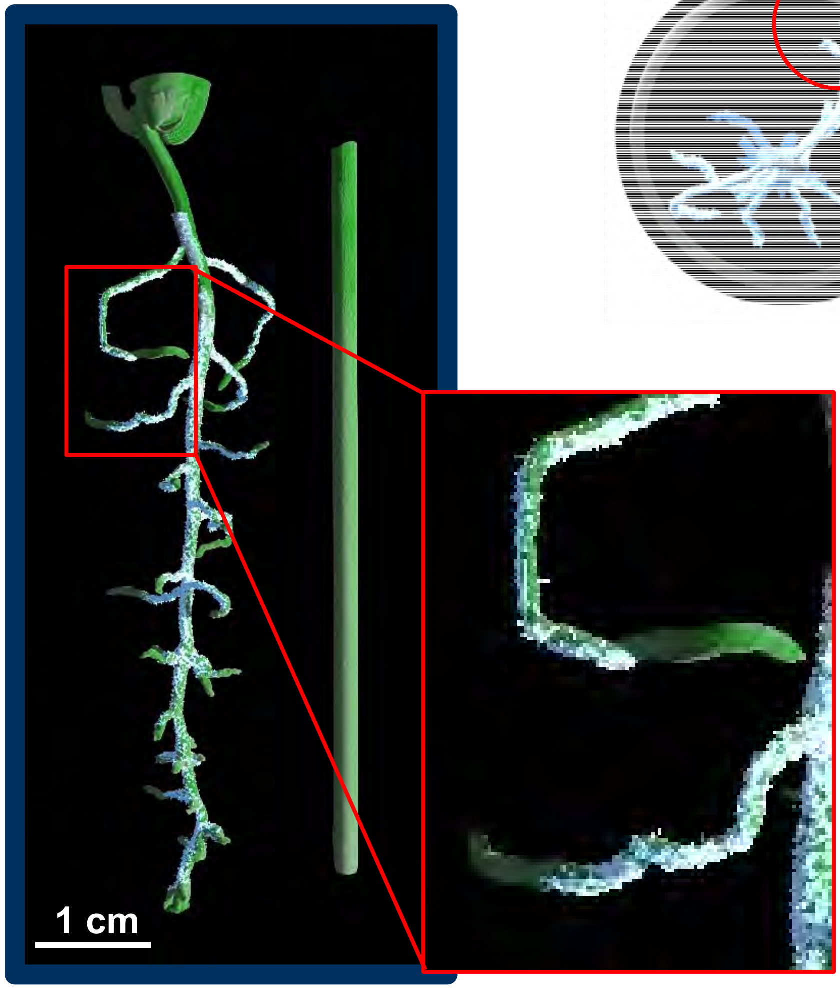
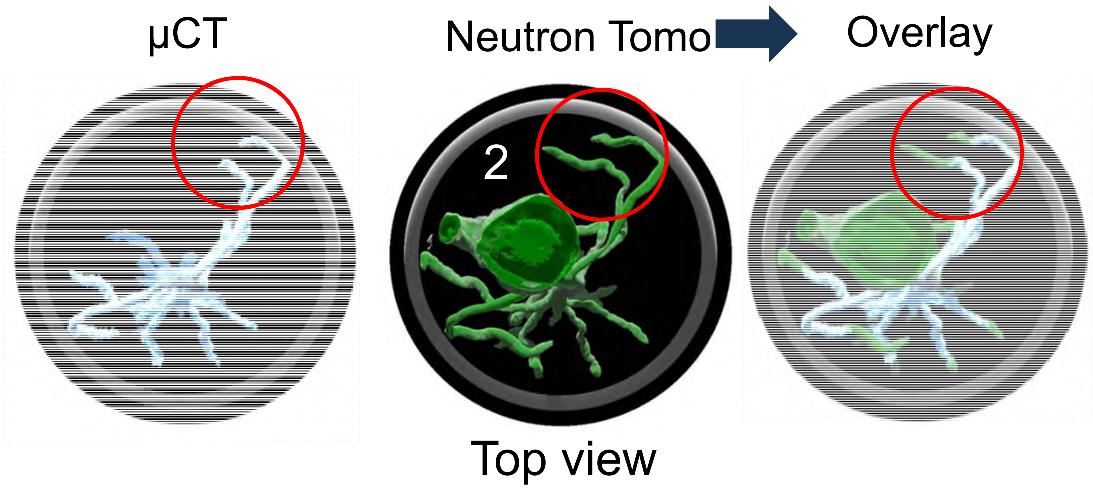
Co-registration – Bean seedling



Christian Tötzke et al., manuscript in preparation

Difference in architecture → Root Growth

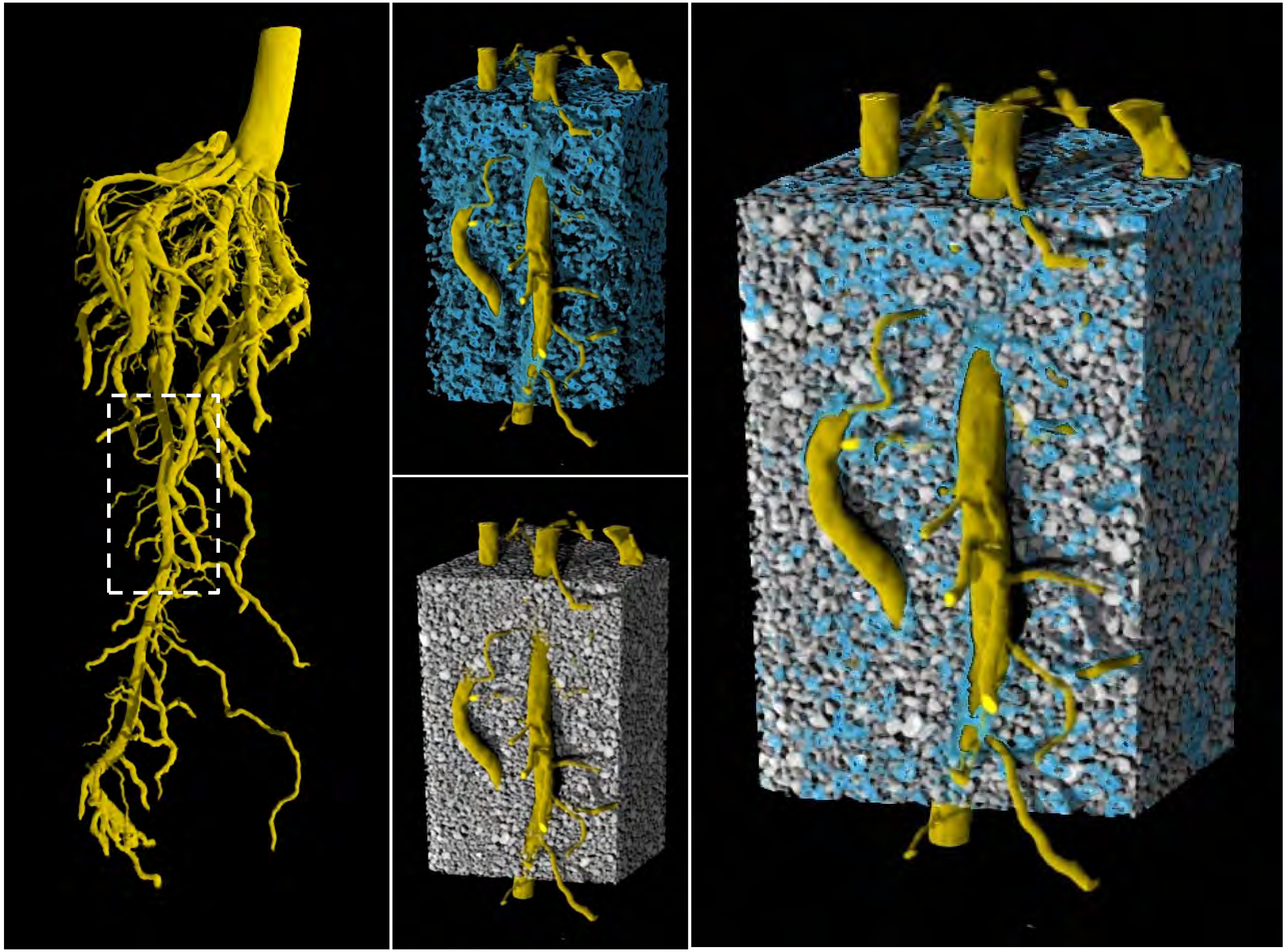




3 days time shift between measurements
→ Root development
→ **Longitudinal growth ~ 6mm**

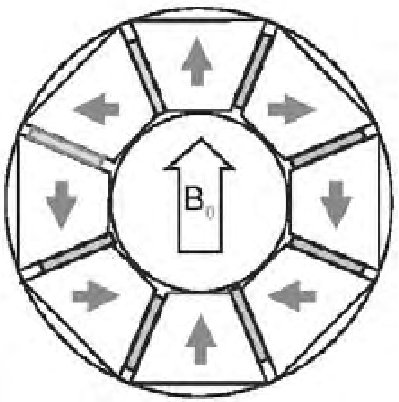
Christian Tötzke et al., manuscript in preparation, 2017

Combined results from Neutrons and X-rays



Christian Tötzke et al., manuscript in preparation, 2019

Mobile MRI possible at NI facility



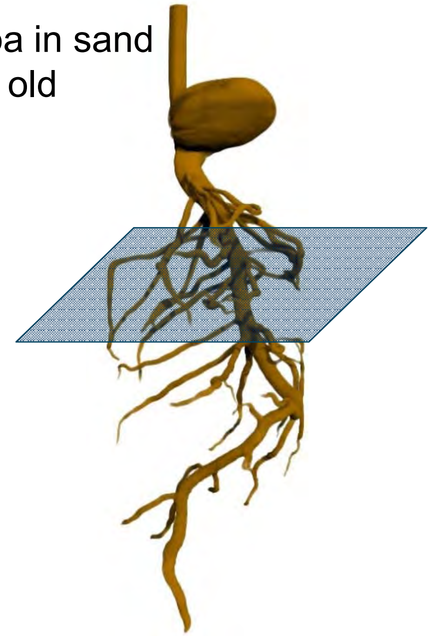
- Based on permanent magnets
- Very recent development
- MRI sequences and operation by S. Haber-Pohlmeier (RWTH) and A. Pohlmeier (FZJ)

S. Haber-Pohlmeier et al., Vadose Zone Journal, 2019

Add MRI relaxation time maps –
work together with Sabina Haber-Pohlmeier & Andreas Pohlmeier

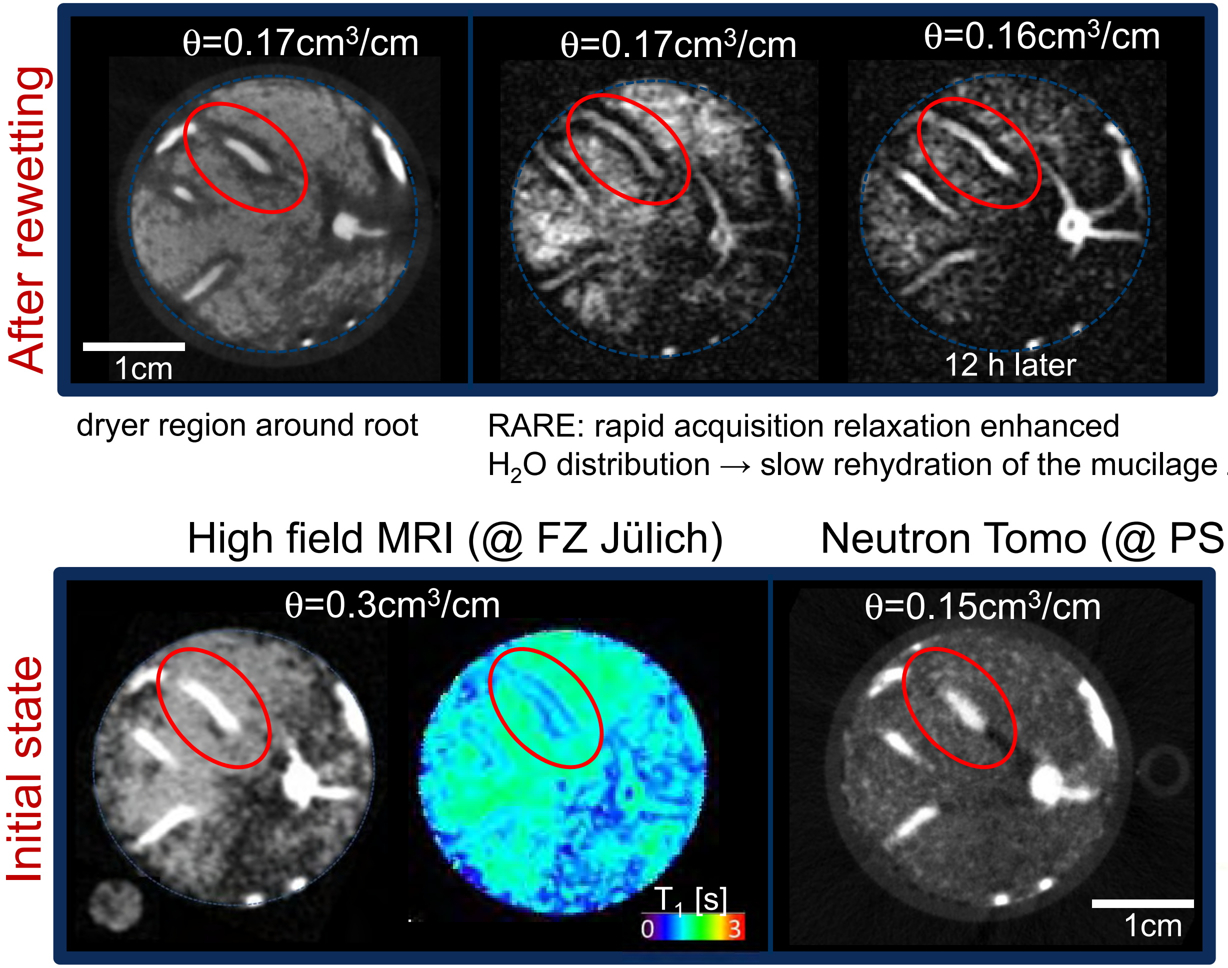
Rhizosphere during drying-rewetting cycle

Vicia faba in sand
2 weeks old



Neutron Tomo (@ PSI) Low field MRI (@PSI)

High field MRI (@ FZ Jülich) Neutron Tomo (@ PSI)



dryer region around root

RARE: rapid acquisition relaxation enhanced
H_2O distribution → slow rehydration of the mucilage zone

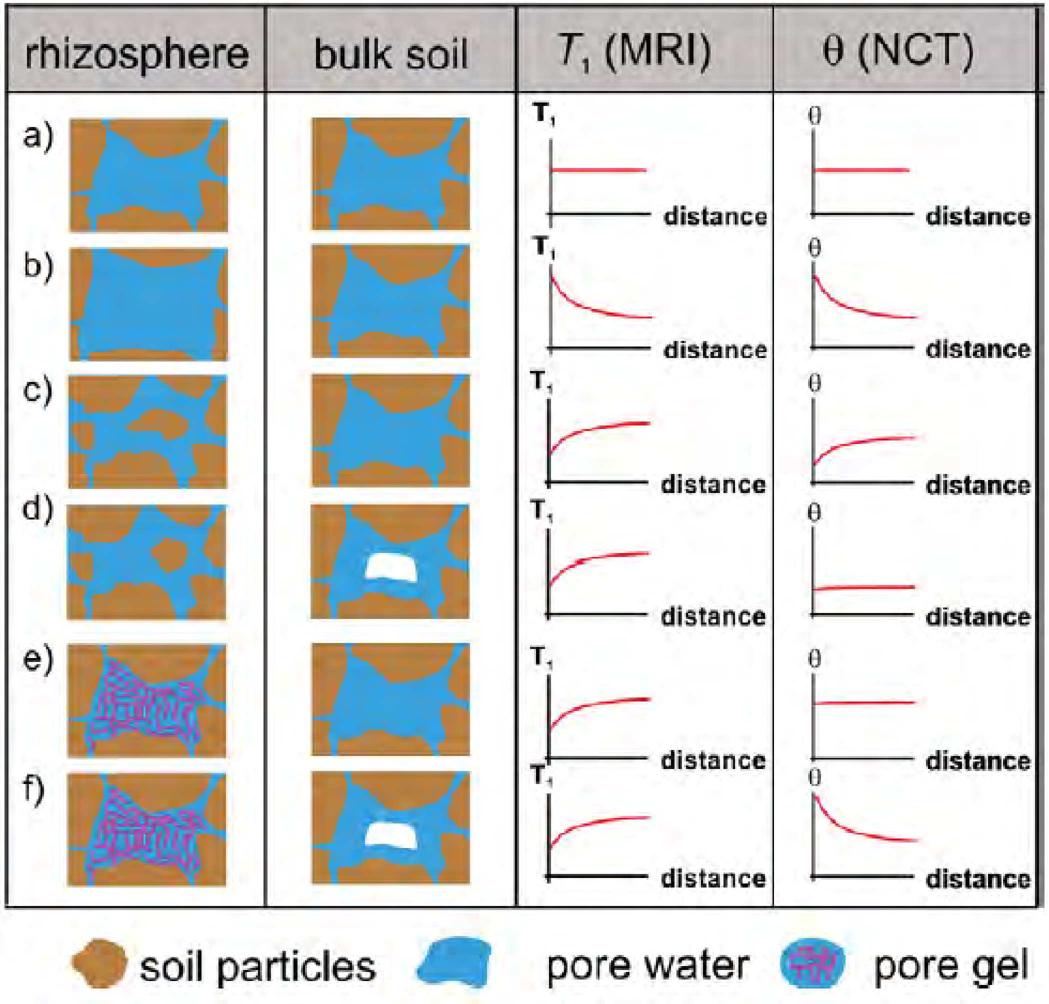
Spin Echo Multi-Slice
→uniform H_2O distribution

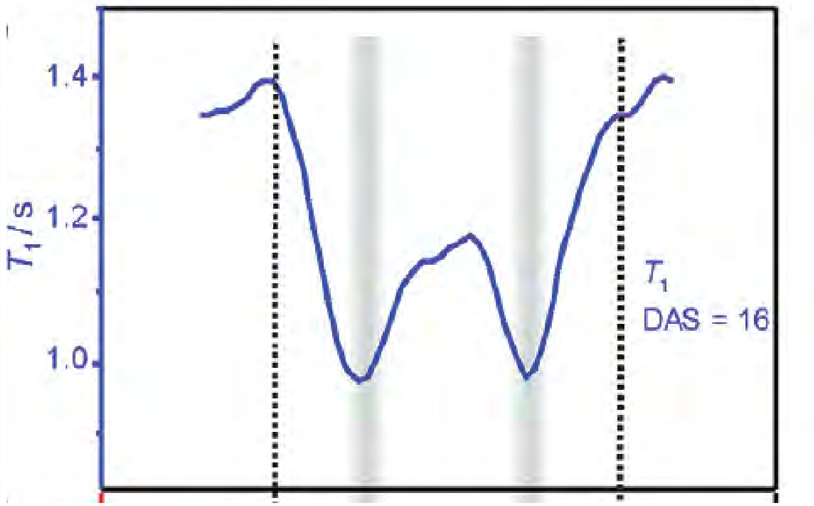
T1 map, relaxation time
→ different water environment

uniform water distribution

Similar in S. Haber-Pohlmeier et al., Vadose Zone Journal, 2019

MRI adds relaxation time info (and water)

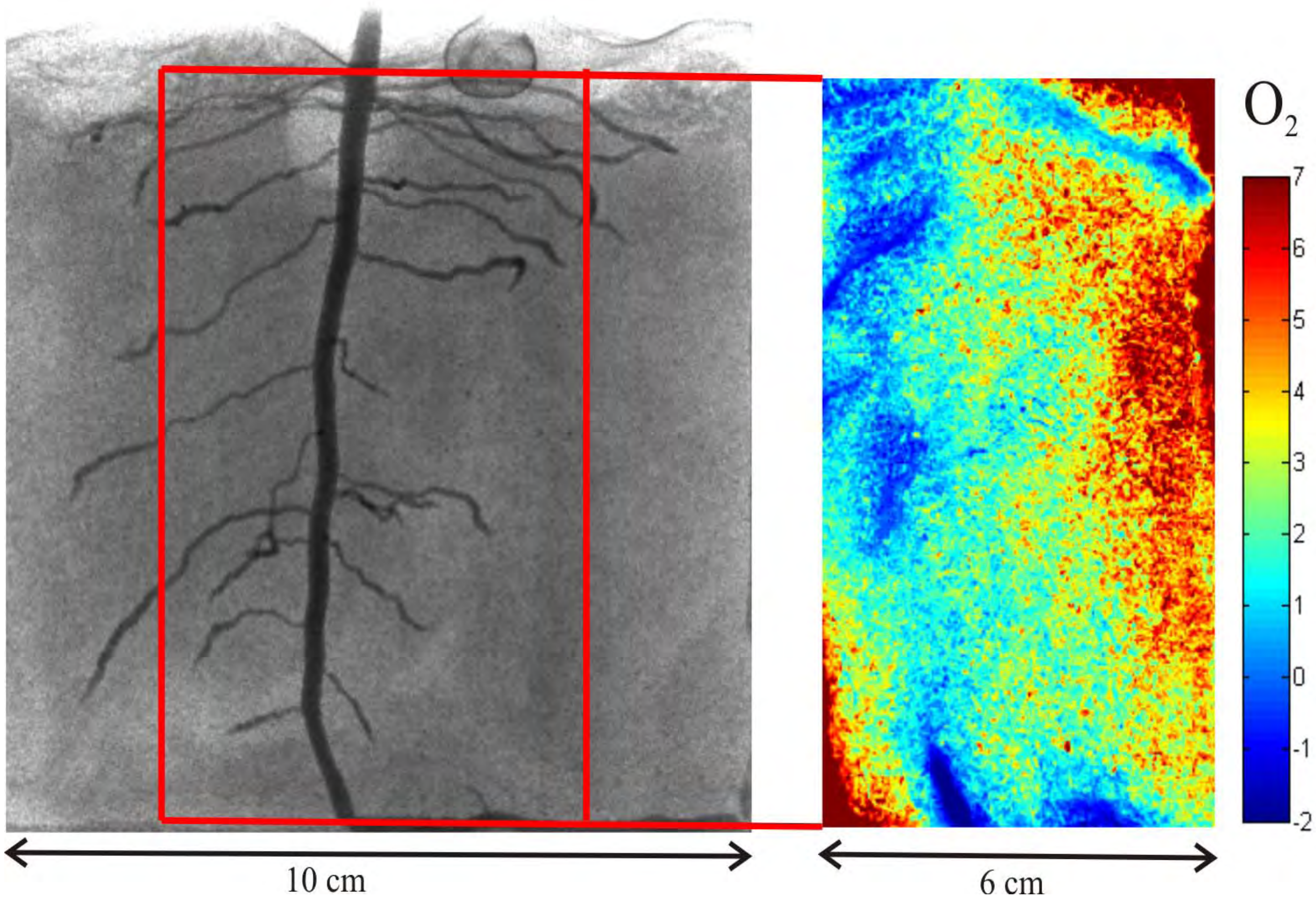




S. Haber-Pohlmeier et al., Vadose Zone Journal, 2019

Combining 2D neutron imaging and Fluorescence Imaging

Combined Neutron Imaging and Fluorescence Imaging: Oxygen



Rudolph et al., *J Soils and Sediments*, 2012

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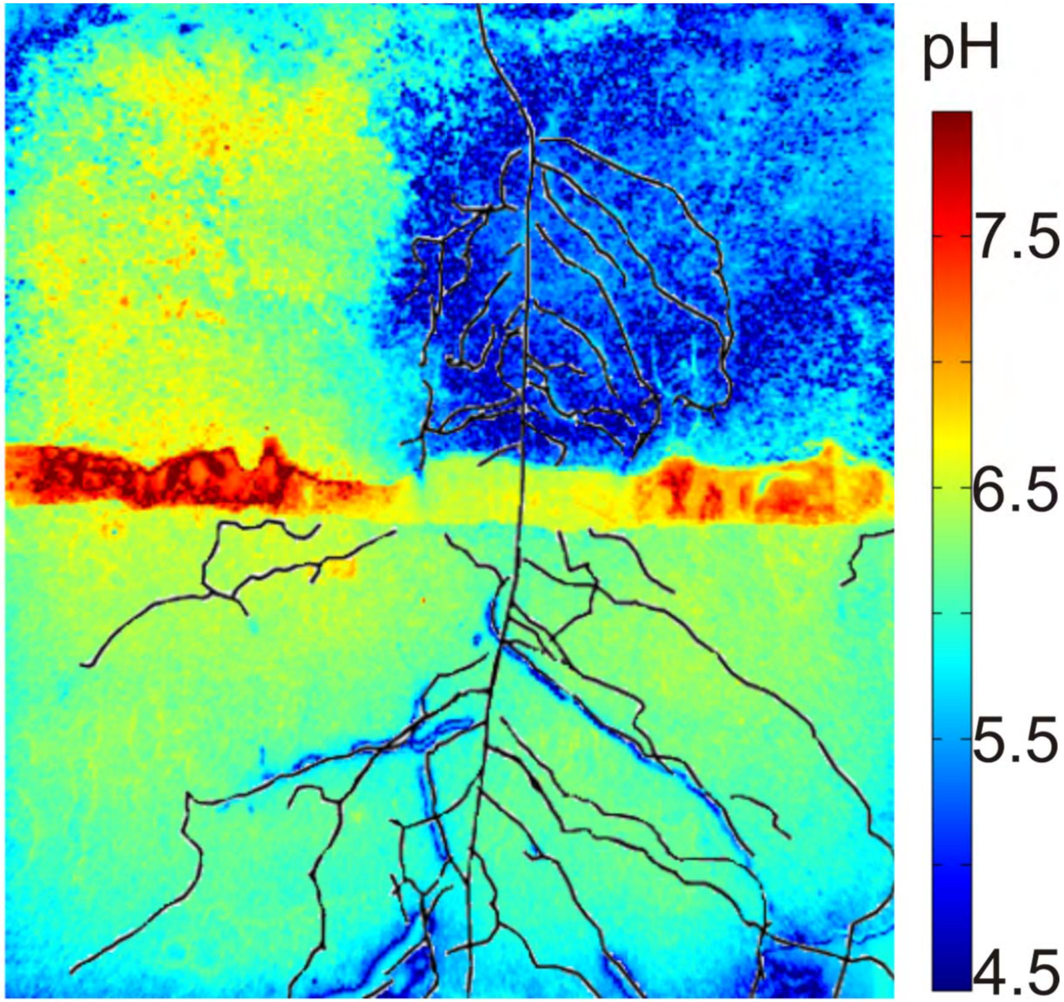
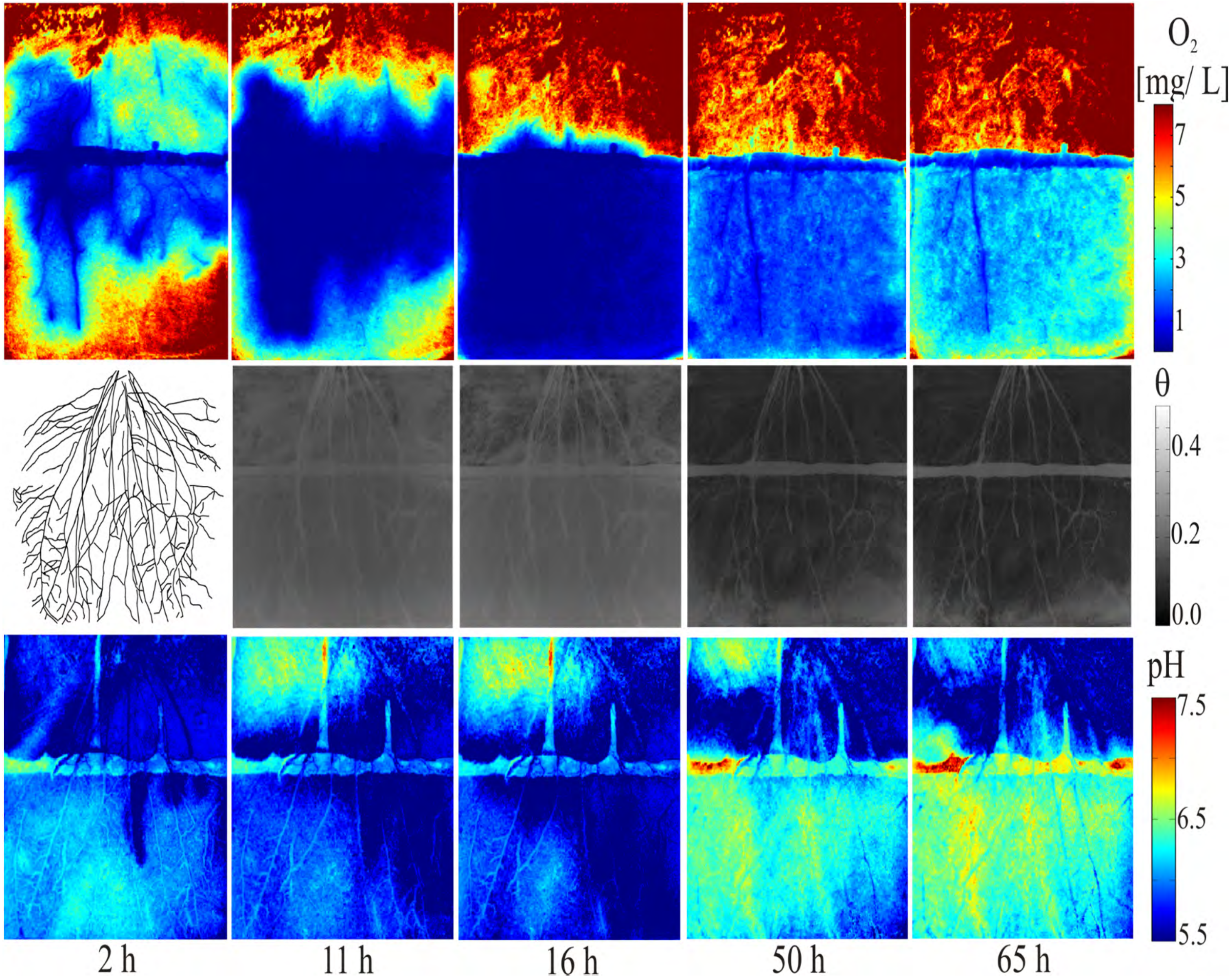
Combined Neutron Imaging and Fluorescence Imaging: pH



Rudolph-Mohr et al., *Annals of Botany*, 2014; Rudolph et al., 2013

Combined Triple Imaging, water, DO, pH



Rudolph-Mohr et al., *J Plant Nutrition and Soil Science,* 2017

Summary 2D

- Root growth
- Infiltration and uptake, local rhizosphere effects?
- Water stress compensation in root system
- Combination with fluorescence imaging adds a hydrochemical dimension

but also

- degradation of chemicals in soil aggregates
- Swelling and water storage in soil ammendments

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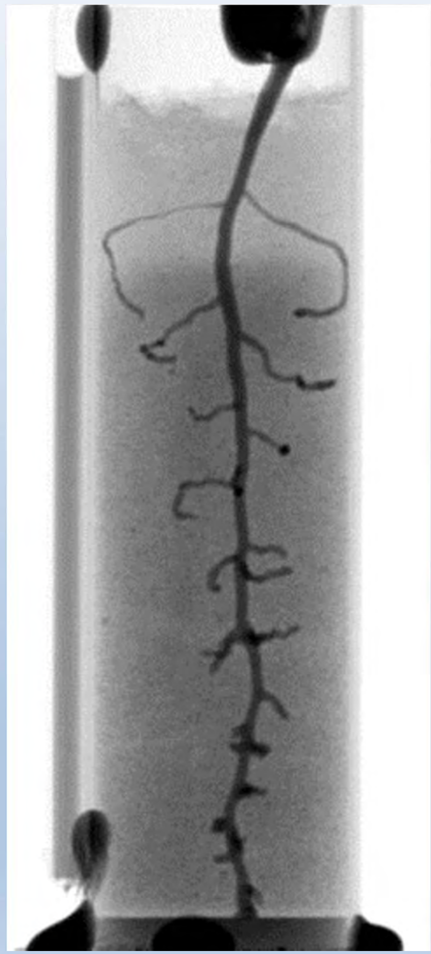
Neutron tomography going dynamic

Capturing 3D water flow in rooted soil

Acquisition time: 100 min



Tötzke et al. (2017), Scientific Reports, 7

Conventional acquisition > 1 hour

- stepwise sample rotation
- several hundreds radiographic projections

→ quasi-static 3D water distribution
→ too slow to capture 3D water dynamics:
e.g. water infiltration, root water uptake

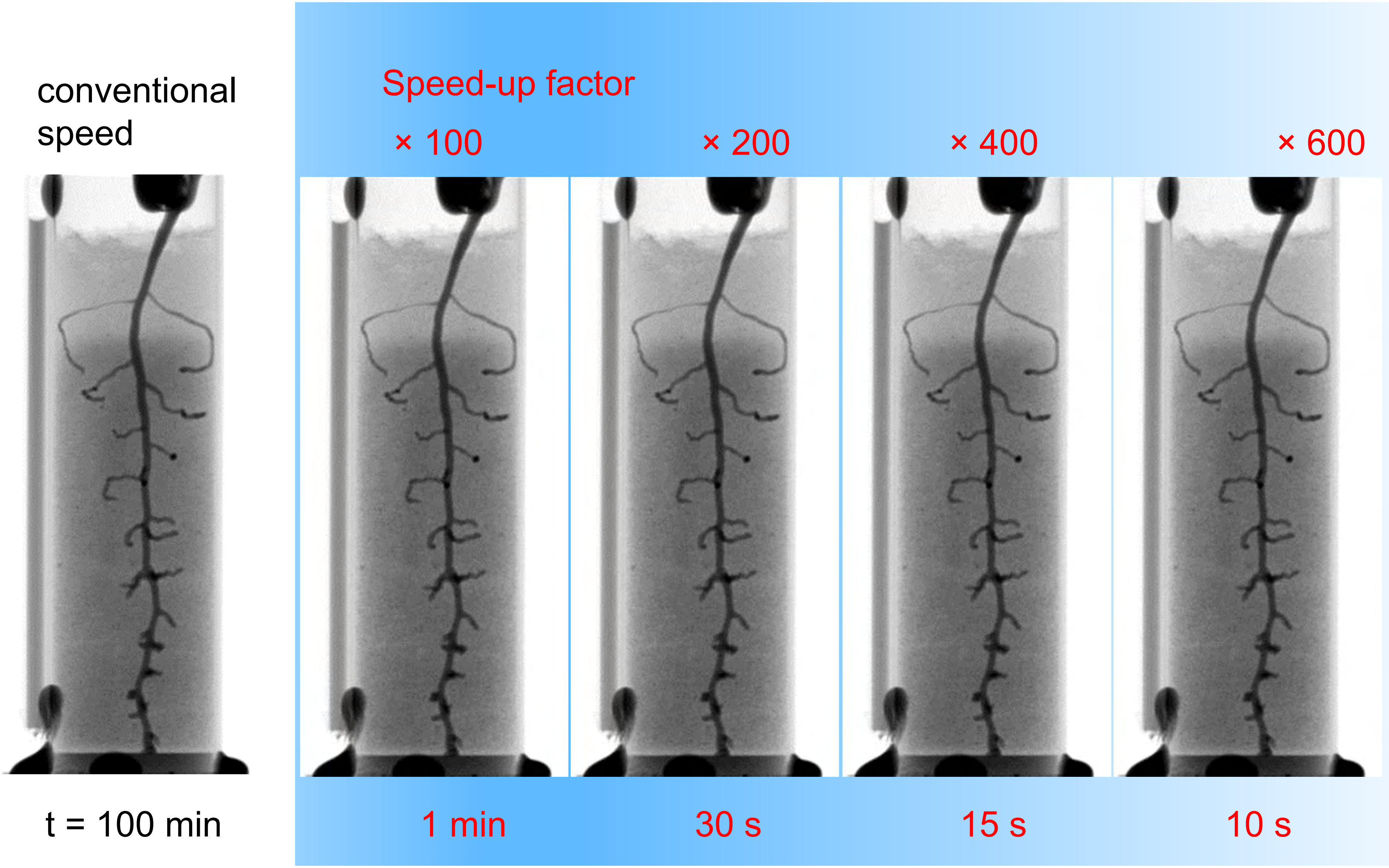
Speed!!! < 1 min
(100 times faster)

Imaging options

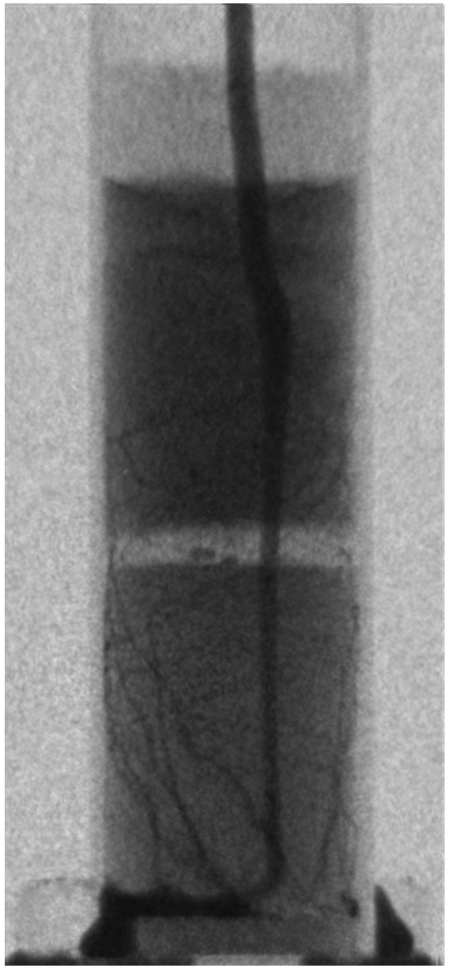
1. neutron flux: source, pin hole/distance
2. signal per pixel: binning
3. rotation: stepwise -> continuous
4. number of projections

Accelerating the acquisition

Tötzke et al. (2017), Scientific Reports, 7



Capturing 3D water flow in rooted soil



600 × faster

Acquisition time: 10 s

Imaging Parameter
Exposure time/projection = 0.05 s
Number of projections = 200
Pixel size = 55 µm
3x3 Binning → 165 µm
CONRAD position: 2
Distance (pinhole-detector) L = 5 m
Pinhole D = 3 cm
L/D = 167

Tötzke et al. (2017), Scientific Reports, 7

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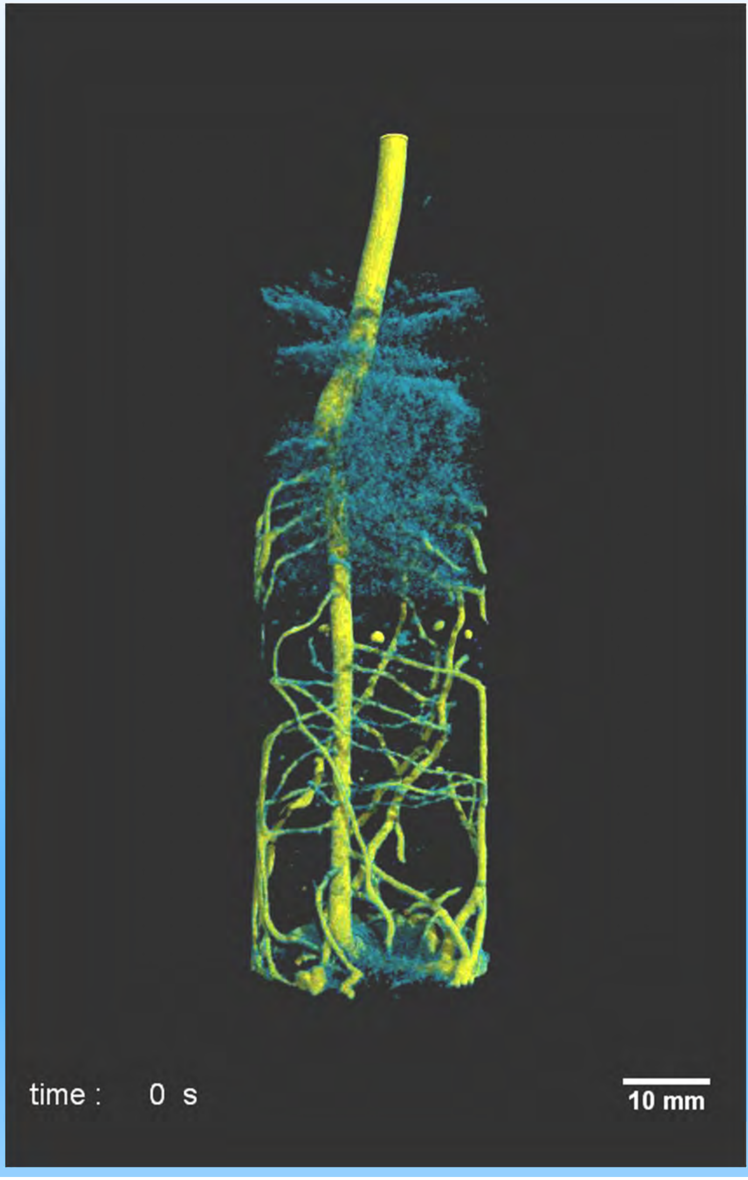
Capturing 3D water flow in rooted soil - lupin



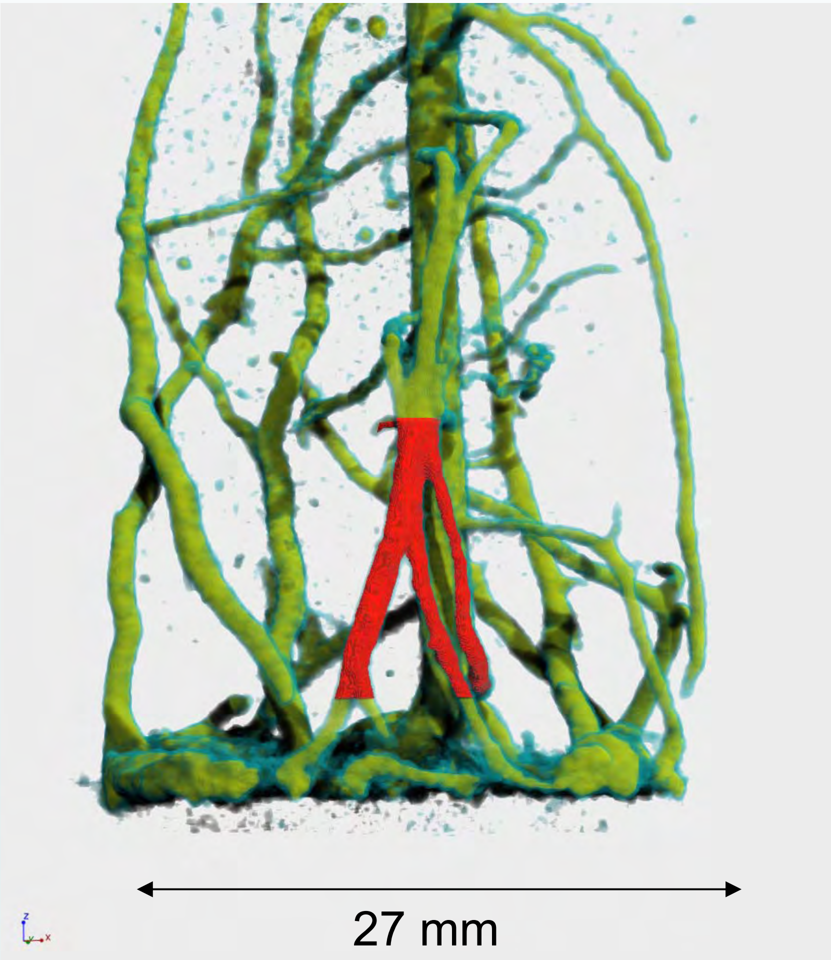
1. D_2O infiltration experiment

Acquisition time: 10 s

- D_2O injection at bottom
- Replacement of H_2O
- Ascending water front
- Stop at hydraulic barrier

*Tötzke et al. (2017), Scientific Reports **7***

Water (D_2O) uptake by lupine roots



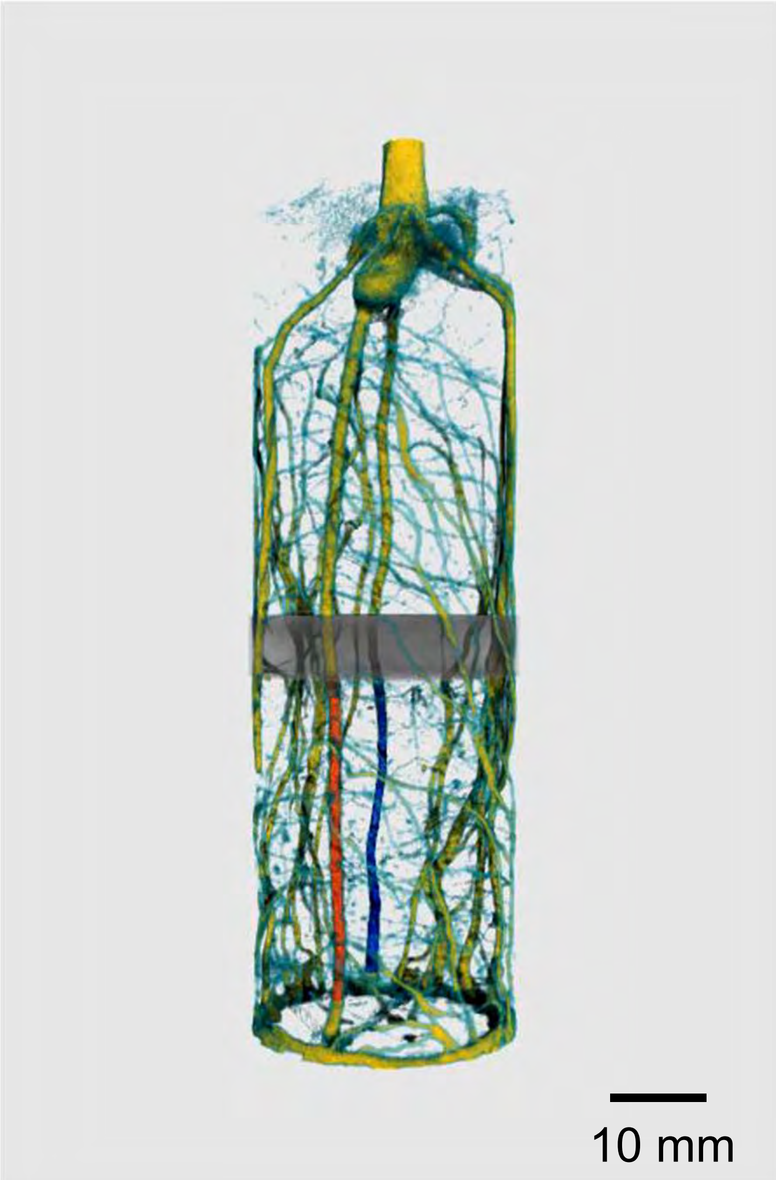
Tötzke et al. (2017), Scientific Reports, 7

Root uptake

10 min

after D_2O injection

Water (D_2O) uptake by maize roots



2. D_2O infiltration experiment

Acquisition time: 1 min
Resolution: 110 µm/pixel

- D_2O injection at bottom
- Ascending water front
- Root uptake

Tötzke et al. (2019), in preparation

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Water (D_2O) uptake by another maize plant

3D maize root system

3. D_2O infiltration experiment
+ stronger uptake

$\Delta\mu$ [cm^{-1}]

+ 0.2 - 0.7

30 mm

time 0 min

Tötzke et al., publication in preparation

Summary 3D

- Combination of NR with XCT and/or MRI possible and beneficial
- Fast neutron tomography – experimental key for studying 3D water dynamics *in situ*
- Infiltration experiments enhance understanding of rhizosphere hydraulics
- Valuable experimental complement for 3D models simulating root water uptake

- Broad applicability of fast NT to analyze 3D transport processes in porous media (materials - and geoscience)

Tötzke et al. (2019), in preparation

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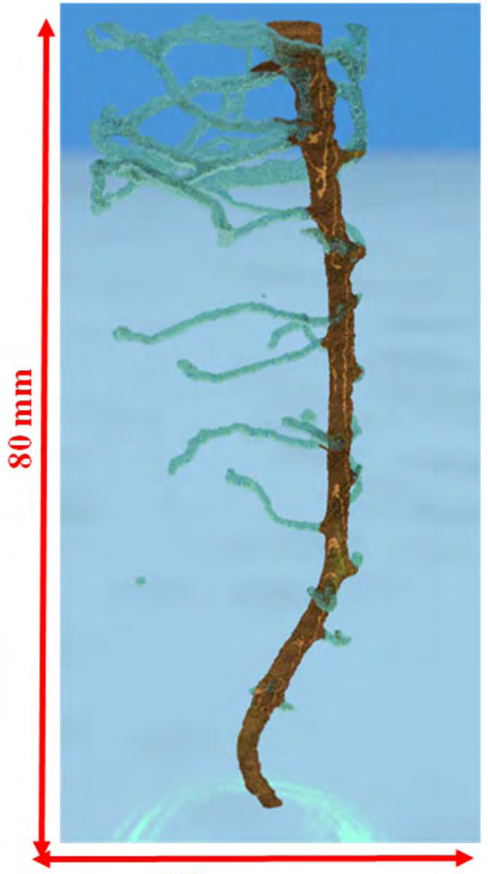
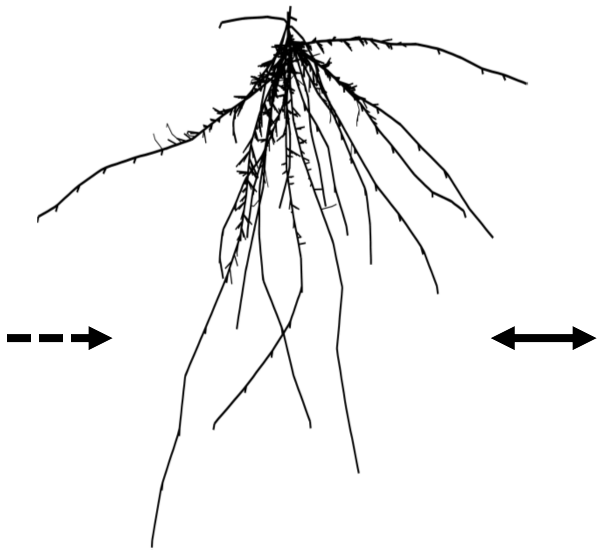
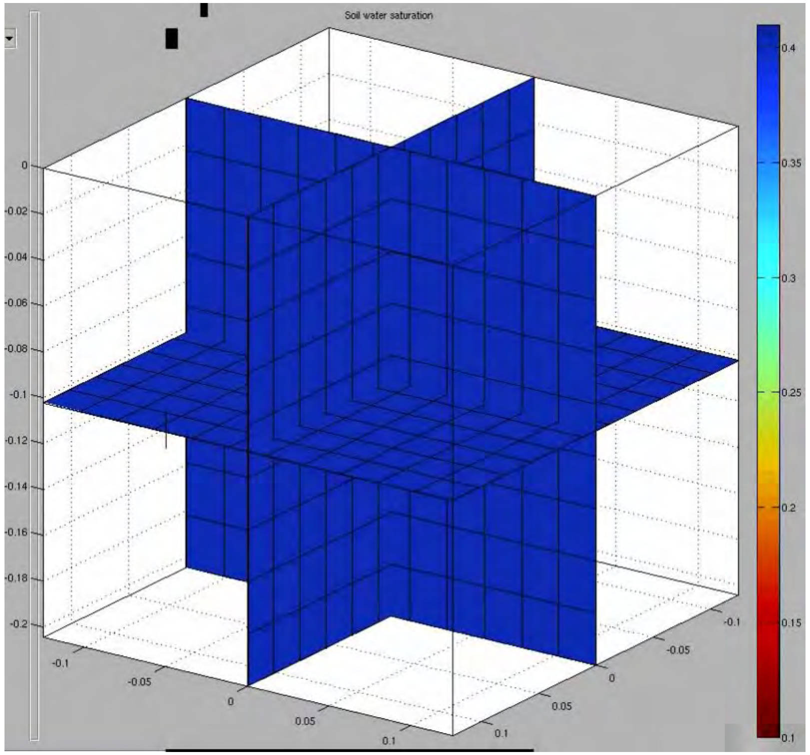
Missing: combination of root structure and numerical simulation of water flow and root uptake (in 3D)



(similar to A. Moradi et al., *New Phytologist*, 2011)

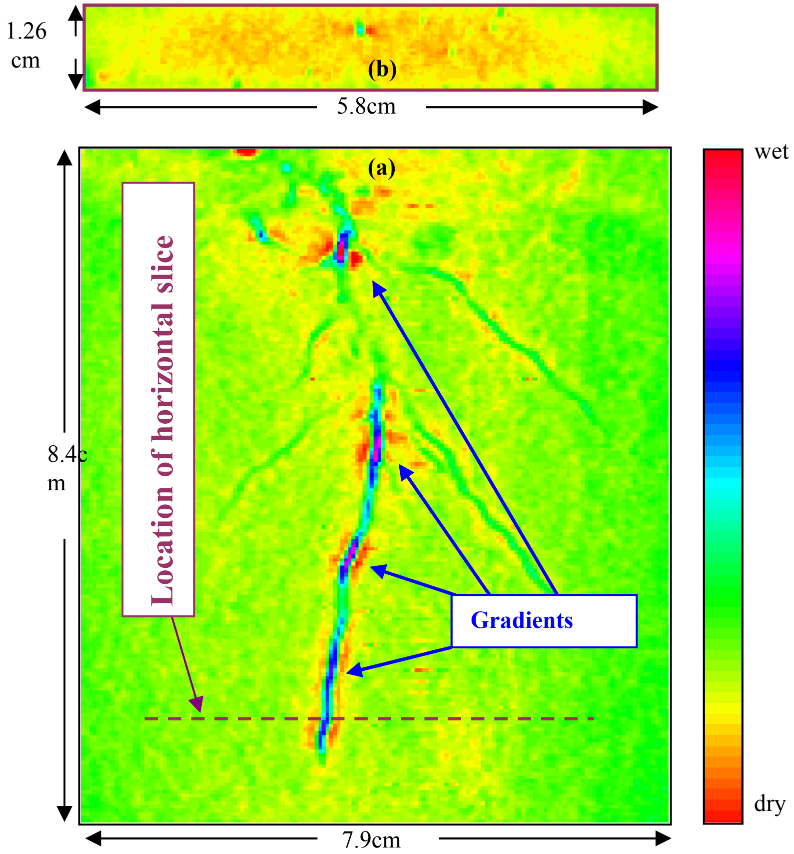




Simulation of root and soil moisture for 5 days,
(Schneider, S. Attinger et al., UFZ, Leipzig, Germany)

Combining some 2D and 3D advantages: Tomography possible for rectangular container

- Root structure
- Both 2D and 3D
- Water distribution dynamics and local water gradients



H. Esser et al., Journal of Plant Nutrition and Soil Science, 2010