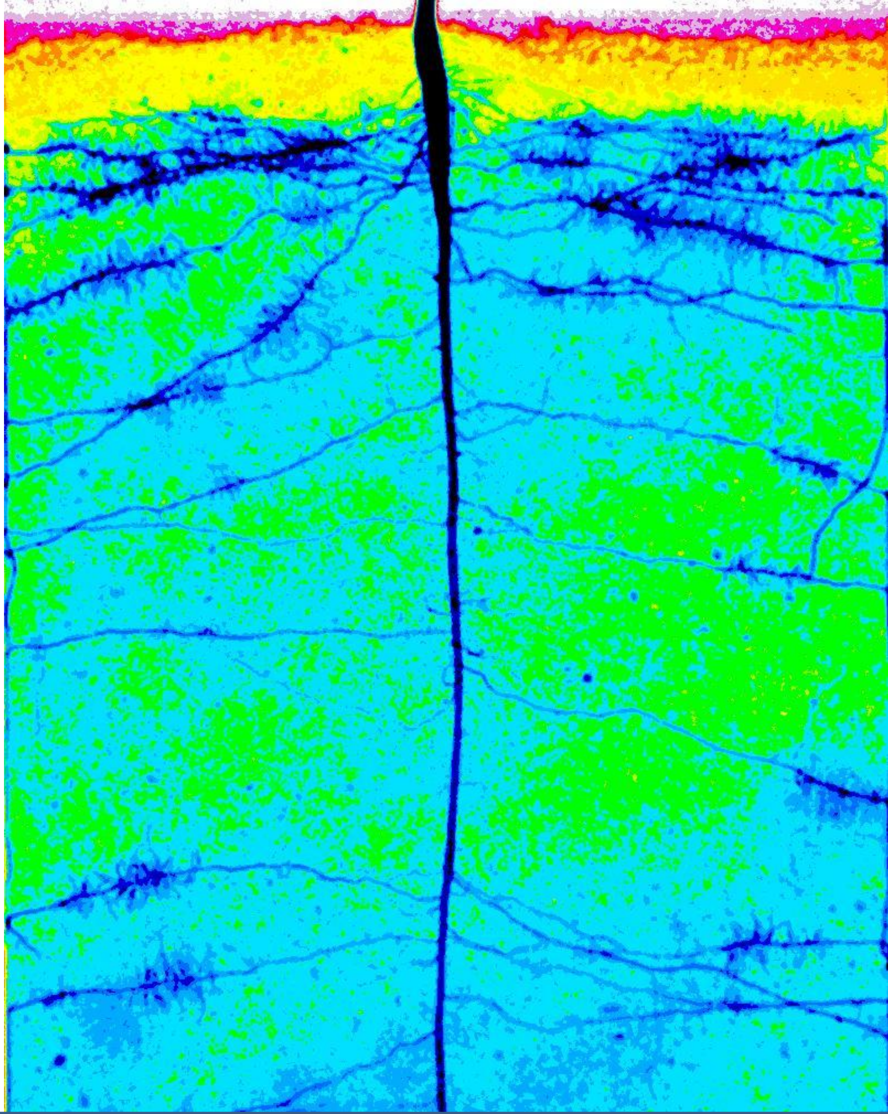
# Imaging water flow in soil and roots

Andrea Carminati
Dept. Soil Hydrology



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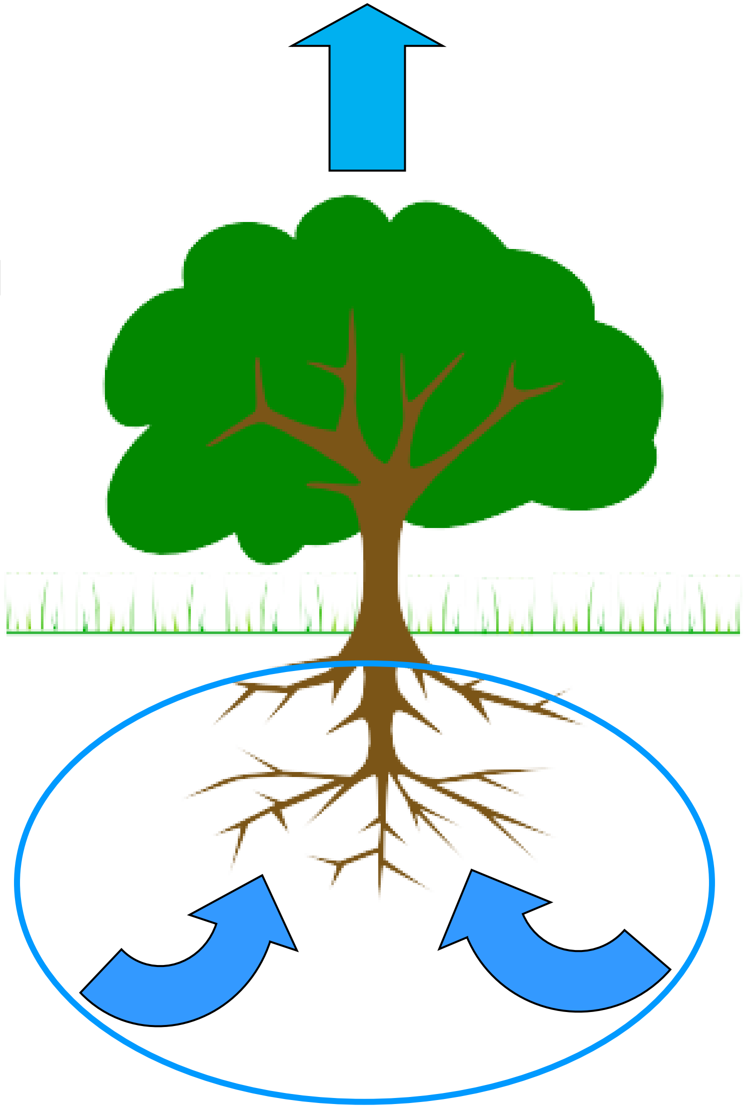
## Significance

- Plants are big water movers. 40% of terrestrial precipitation is transpired by plants
  *Oki & Kanae, Science 2006*

- Water is ***the*** resource for plant growth

## Question

- How "available" is the water in soil to plants?
- How and where do roots take up water?
- How do roots and soil interact



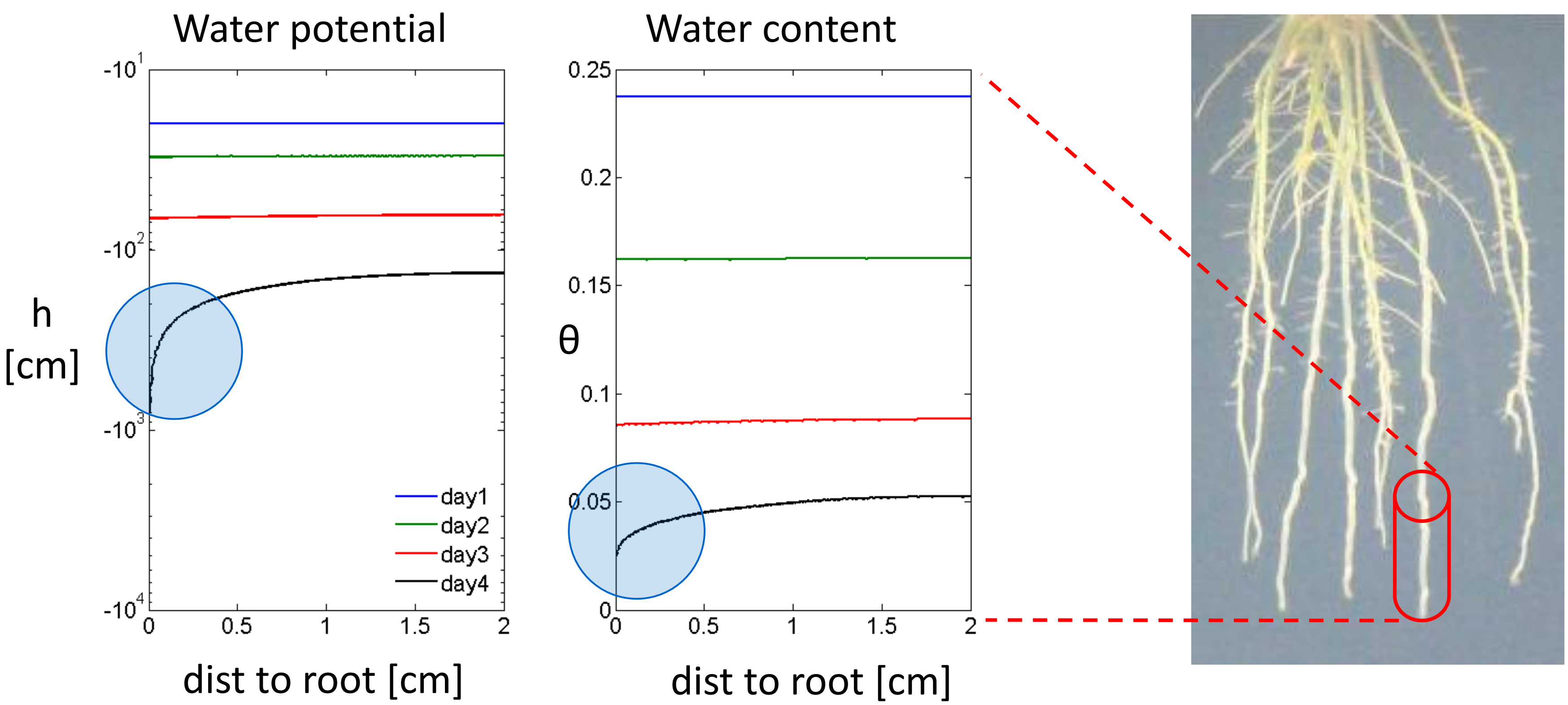
## Why neutrons?

We need to know:

- where roots and water are
- where water flows

# Theory 1: Principles of water flow to a single

Water profiles toward a single root

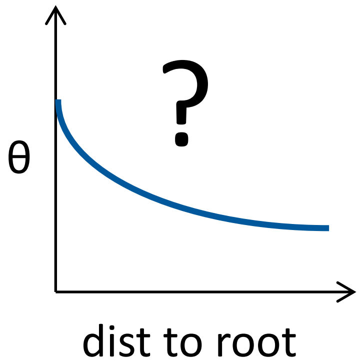


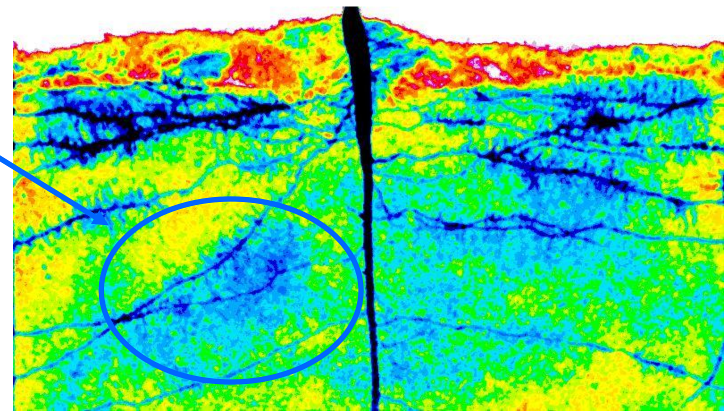

Less water near roots!

# **BUT…** Unexpected water distribution near roots observed with neutron radiography

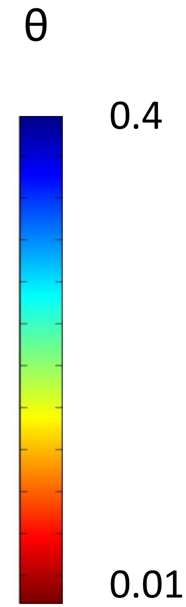


More water near roots

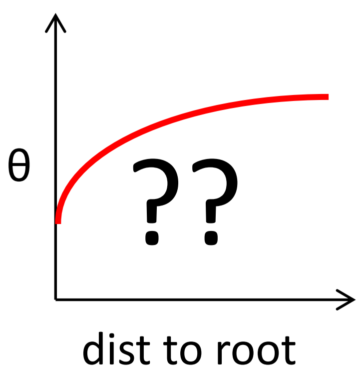


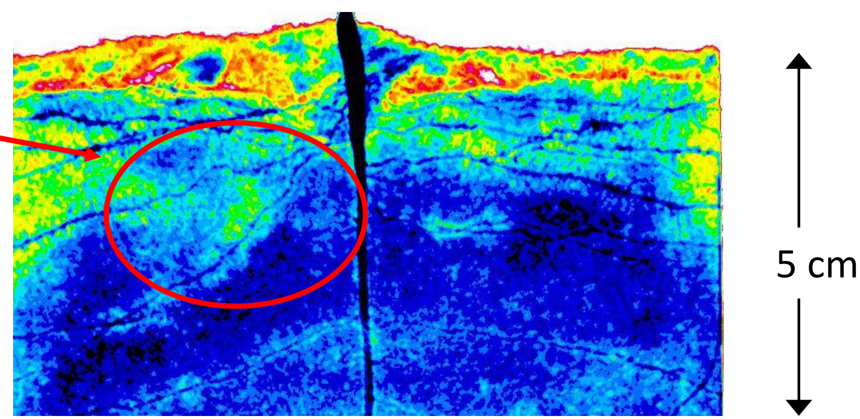



Day 3 -Drying




Less water near roots



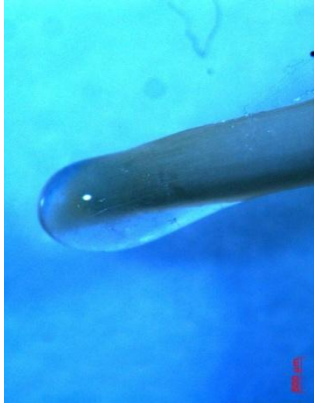



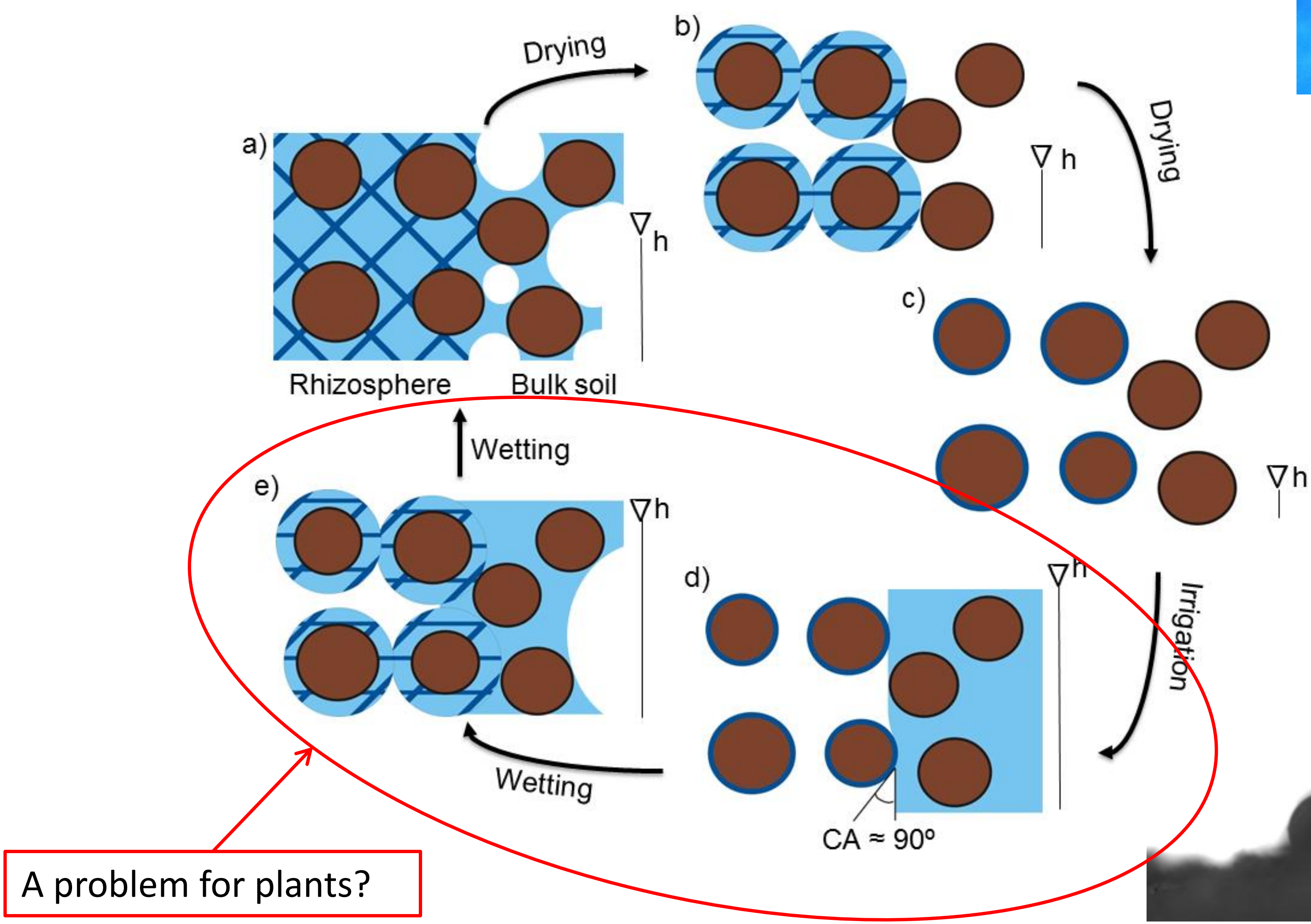

Day 5 -1 hour after rewetting

*Carminati et al, Plant & Soil, 2010*

# Hypothesis: drying/wetting of mucilage exuded by roots

*Carminati, Vadose Zone J, 2012*

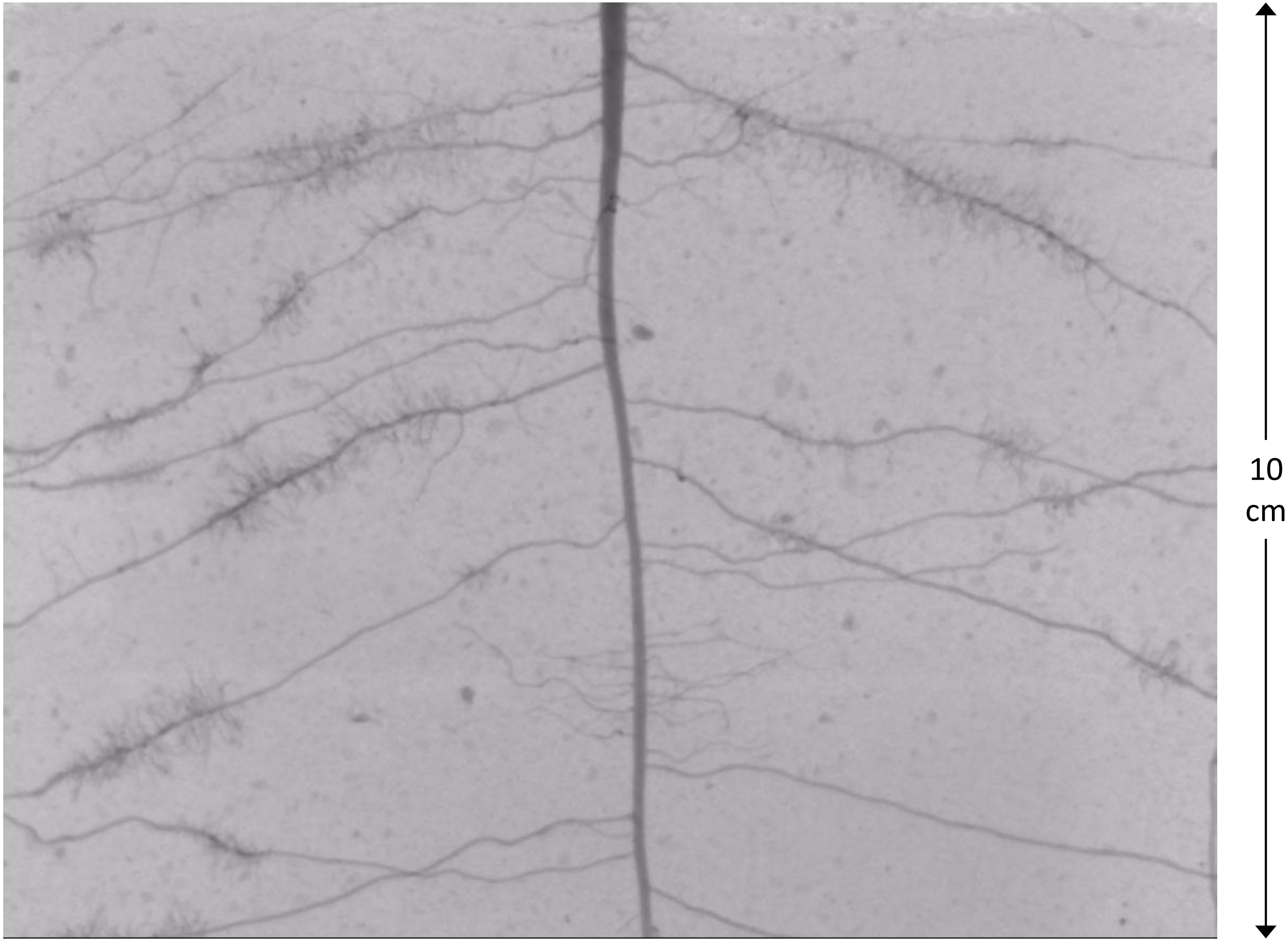





Do roots have access to water after drying?

What is the hydraulic conductivity of the soil near the roots, the *rhizosphere*?

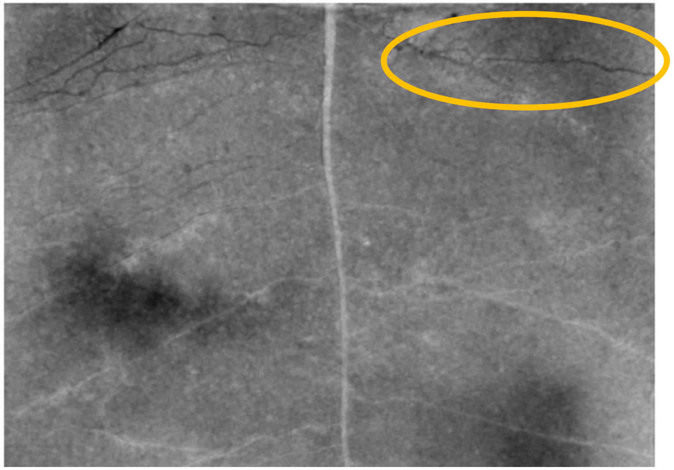
# Water infiltration in soil, rhizosphere, and roots




Dark=Wet   Duration  ~2 hours

# Hydraulic conductivity of the rhizosphere

Root swelling



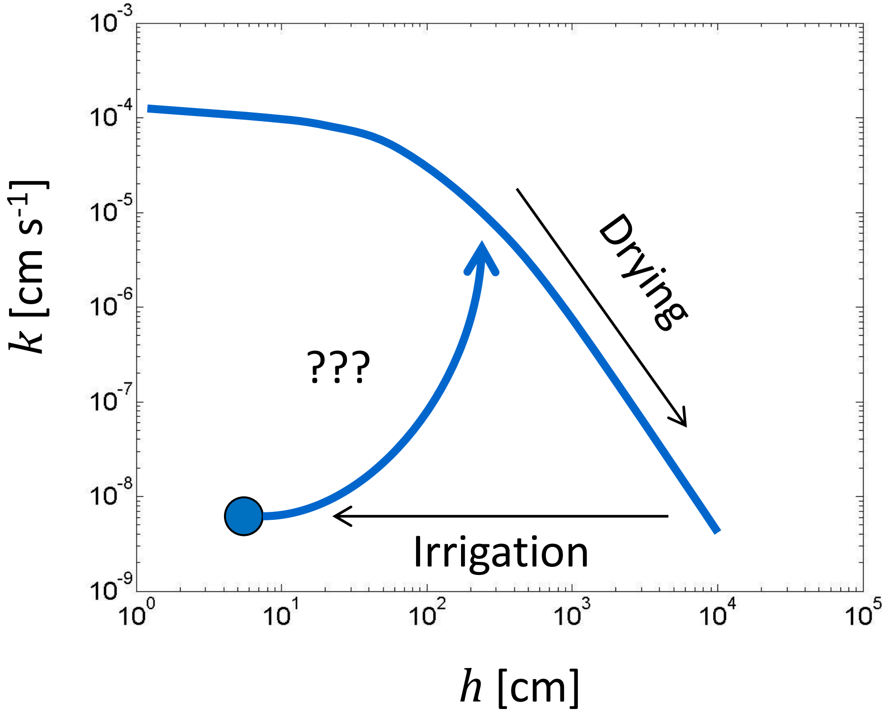
$$q = -k\,\frac{dh}{dr}$$ Darcy law

$h$: water potential [cm]
$dr$: rhizosphere thickness

$$q = \frac{dV_{\mathrm{root}}}{dt}/2\pi r L$$

$r$: root radius
$L$: root length

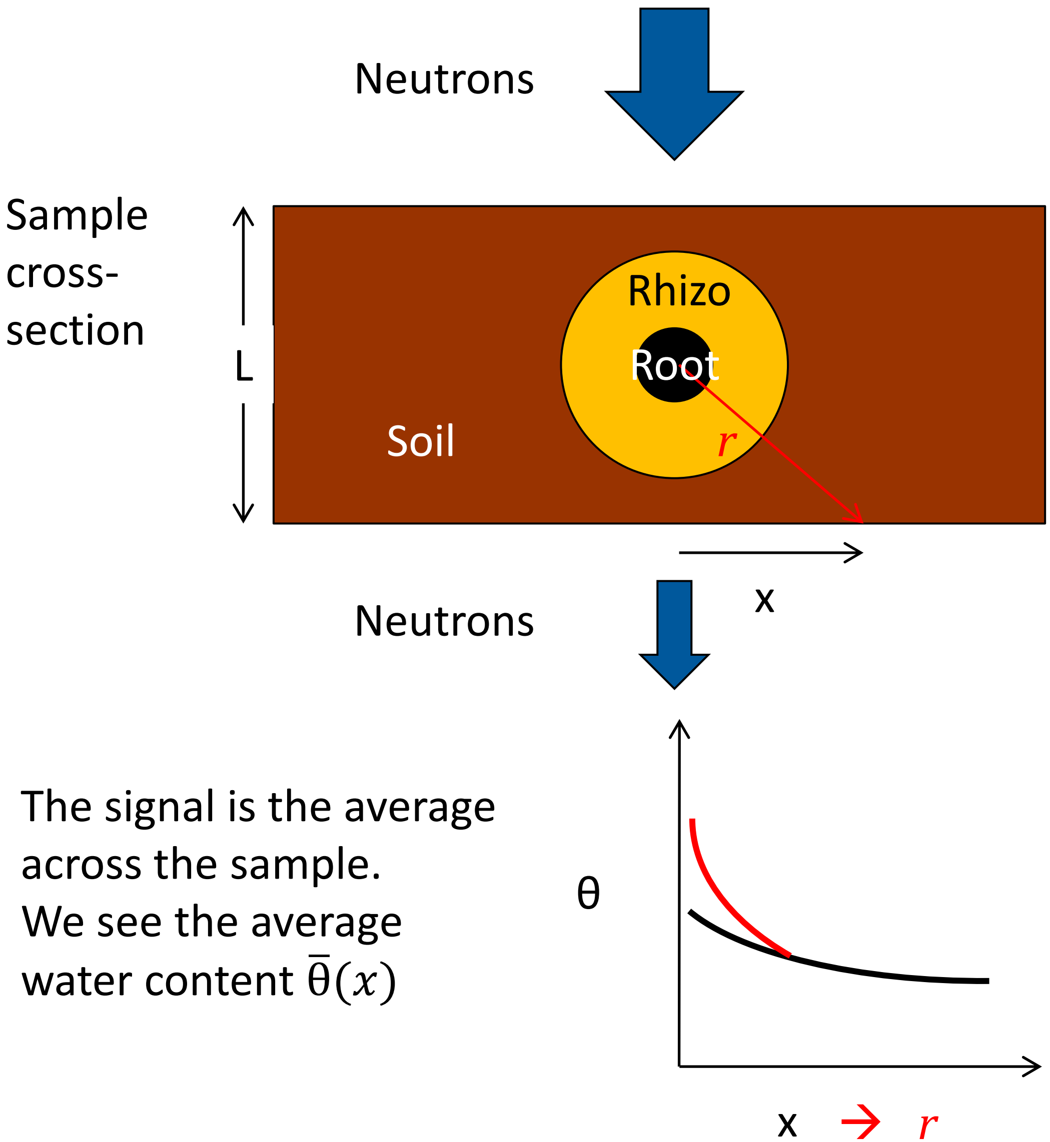
**Idea:** the rate of root swelling depends on the conductivity of the rhizosphere $k_{\mathrm{rhizo}}$




## Goals

1) to calculate $V_{\mathrm{root}}$ from the radiographs
2) to calculate the water content in the rhizosphere $\theta_{\mathrm{rhizo}}$

# Profiles of water content towards the roots




But what is the real 3D water content near the roots?

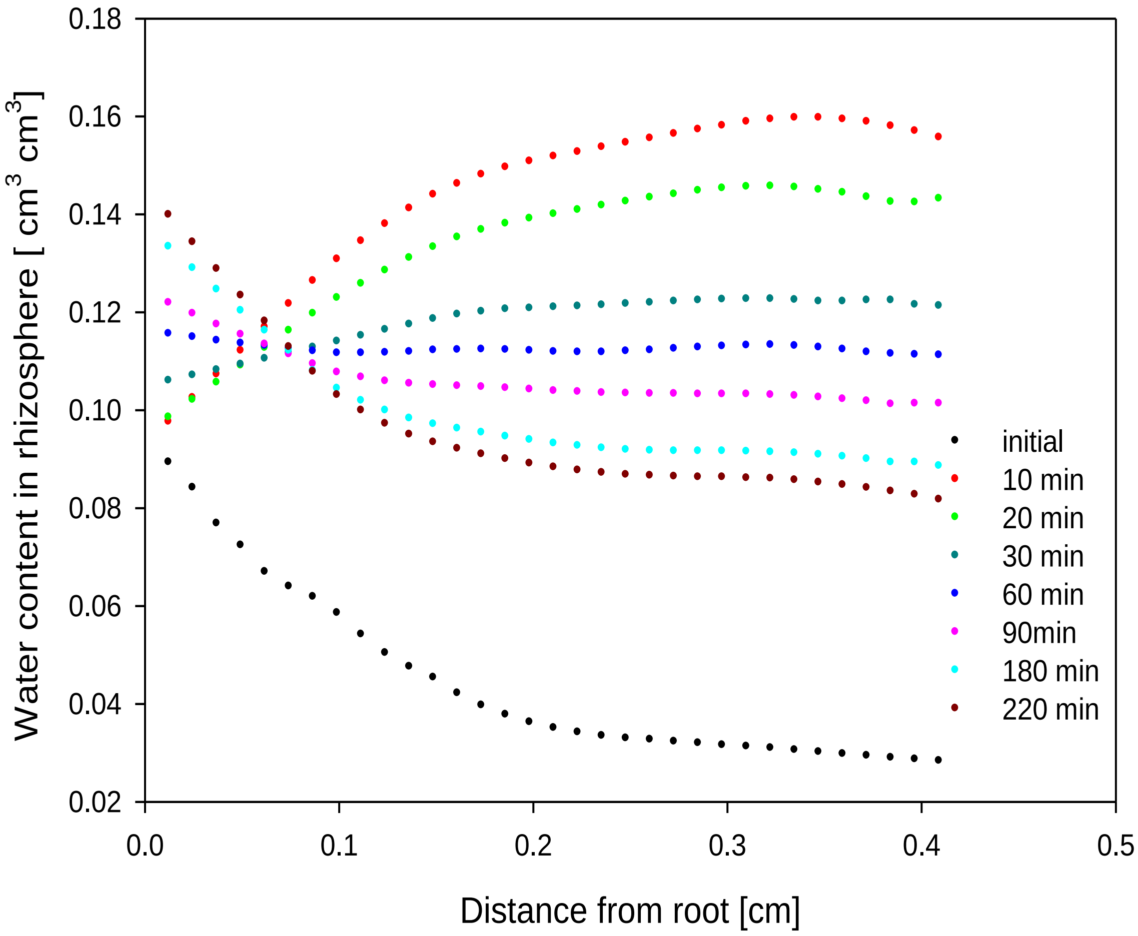
The signal is the average across the sample.
We see the average water content $\bar{\theta}(x)$

Assuming a radial geometry:

$$\bar{\theta}(x) = \frac{1}{L} \int_{x}^{\sqrt{x^2+L^2}} \theta(r) \sqrt{\frac{r^2}{r^2 - x^2}}\, dr$$

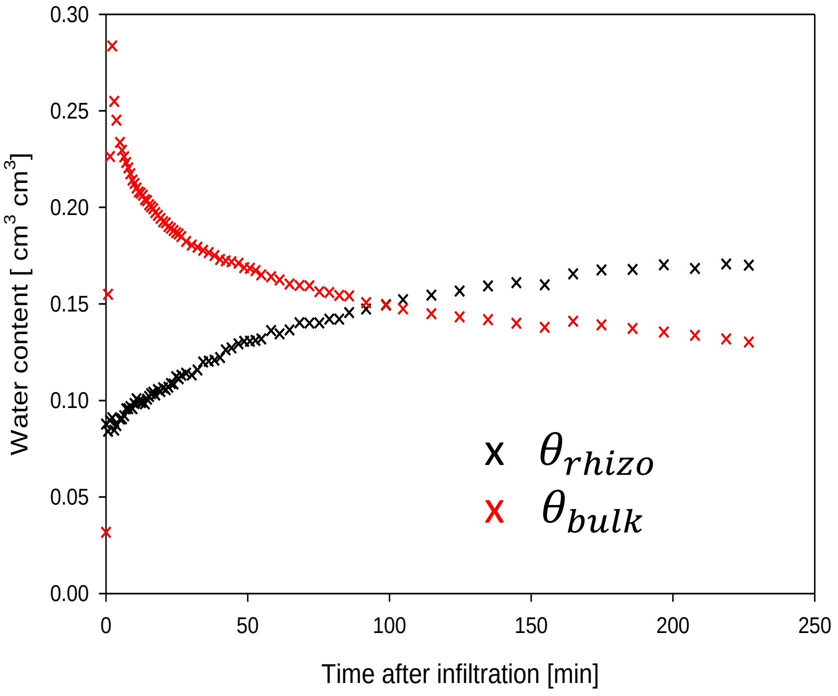
where $\theta(r)$ is the 3D profile to the root

# Corrected 3D profile of water content to roots

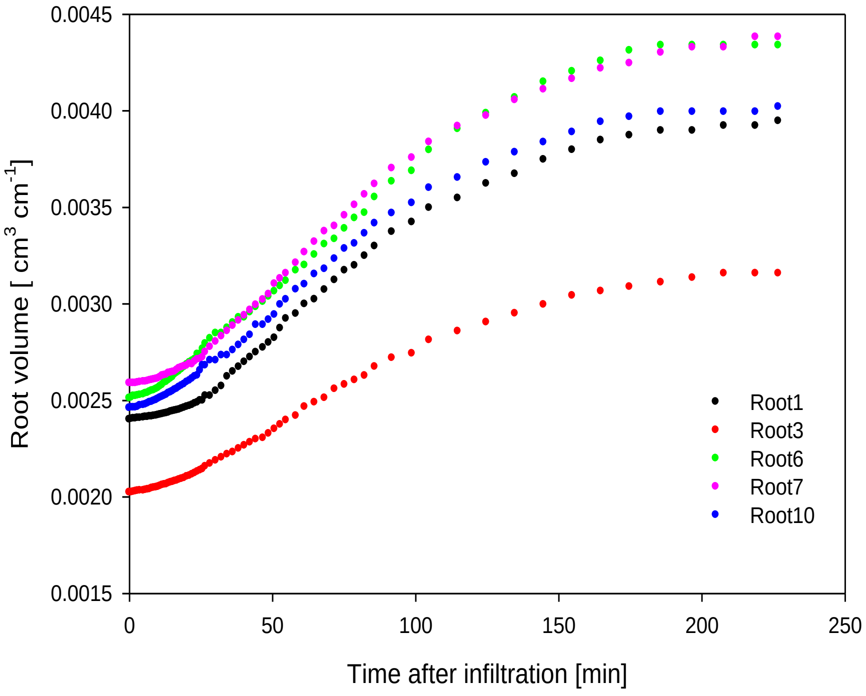


# Corrected 3D profile of water content towards roots

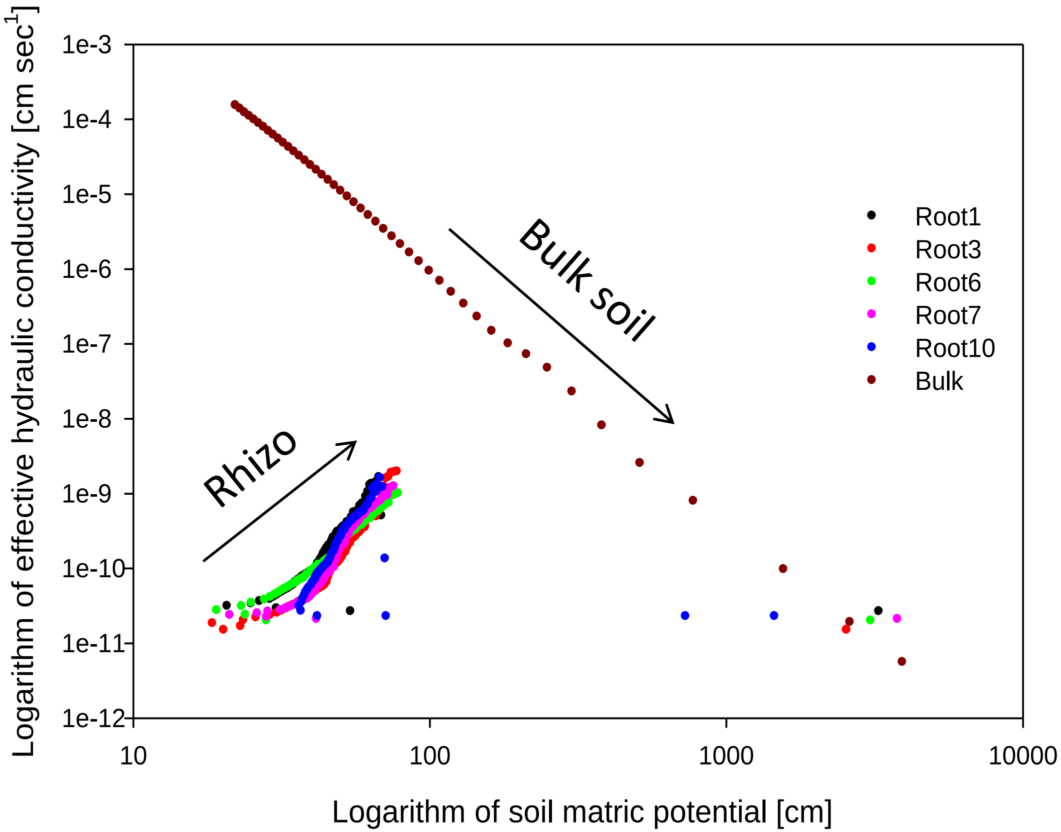
## Water content in rhizosphere and bulk soil




## Root volume



# Hydraulic conductivity of the rhizosphere




After irrigation the conductivity in the rhizosphere is much smaller than in the bulk soil. It partly recovers over time.

## Question:

What are the consequences of the reduced conductivity for root water uptake?

## Method:

Development of a method to measure water flow into roots: local injection of $D_2O$

# Injection of $D_2O$ near roots of transpiring plants

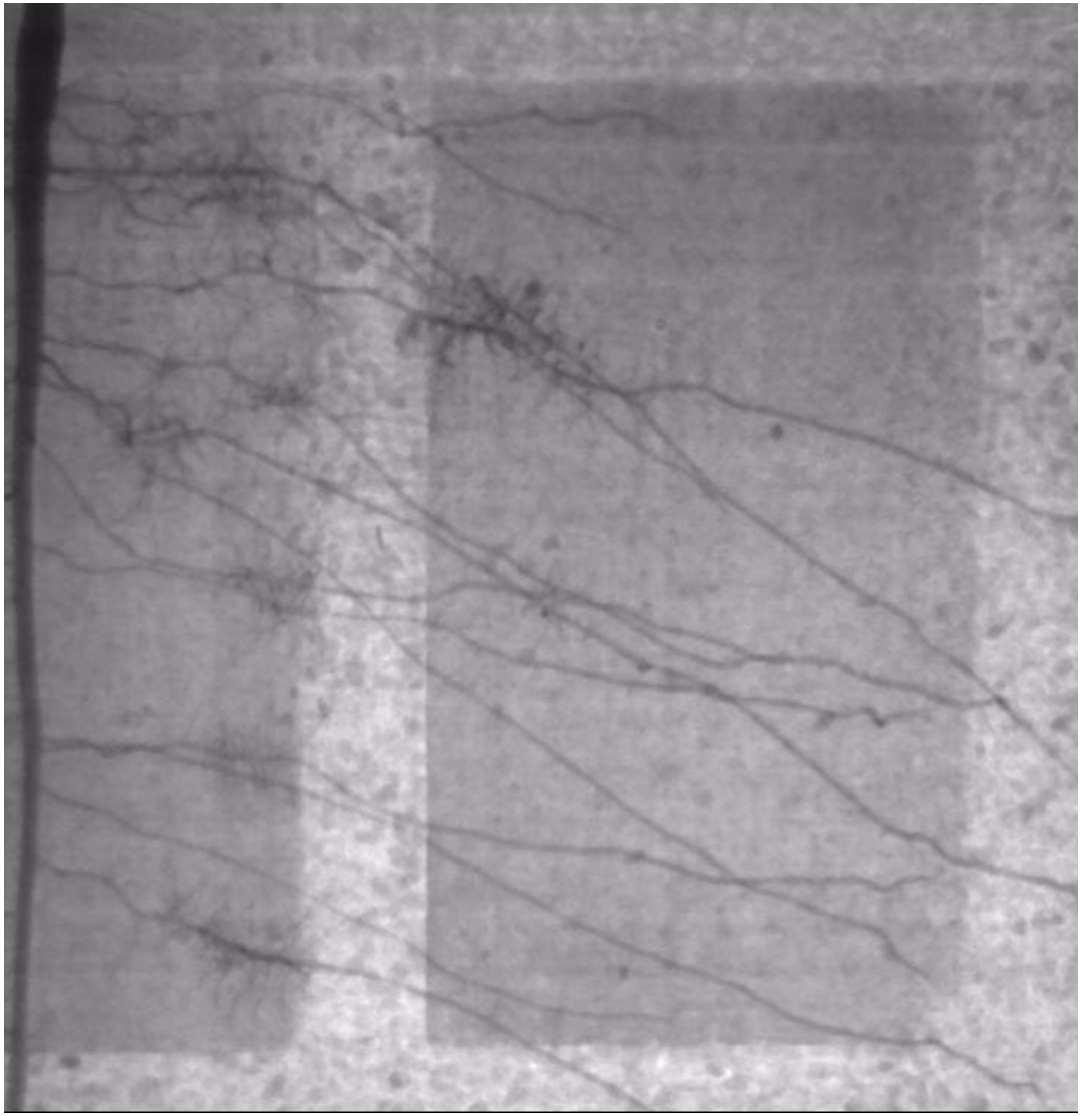
$D_2O$ is injected locally near roots.
Initial θ= 0.07

$D_2O$ distribution in soil and roots is monitored with neutron radiography.

Dark = $H_2O$

Bright = $D_2O$

1 s in movie ≈
1 min in real time

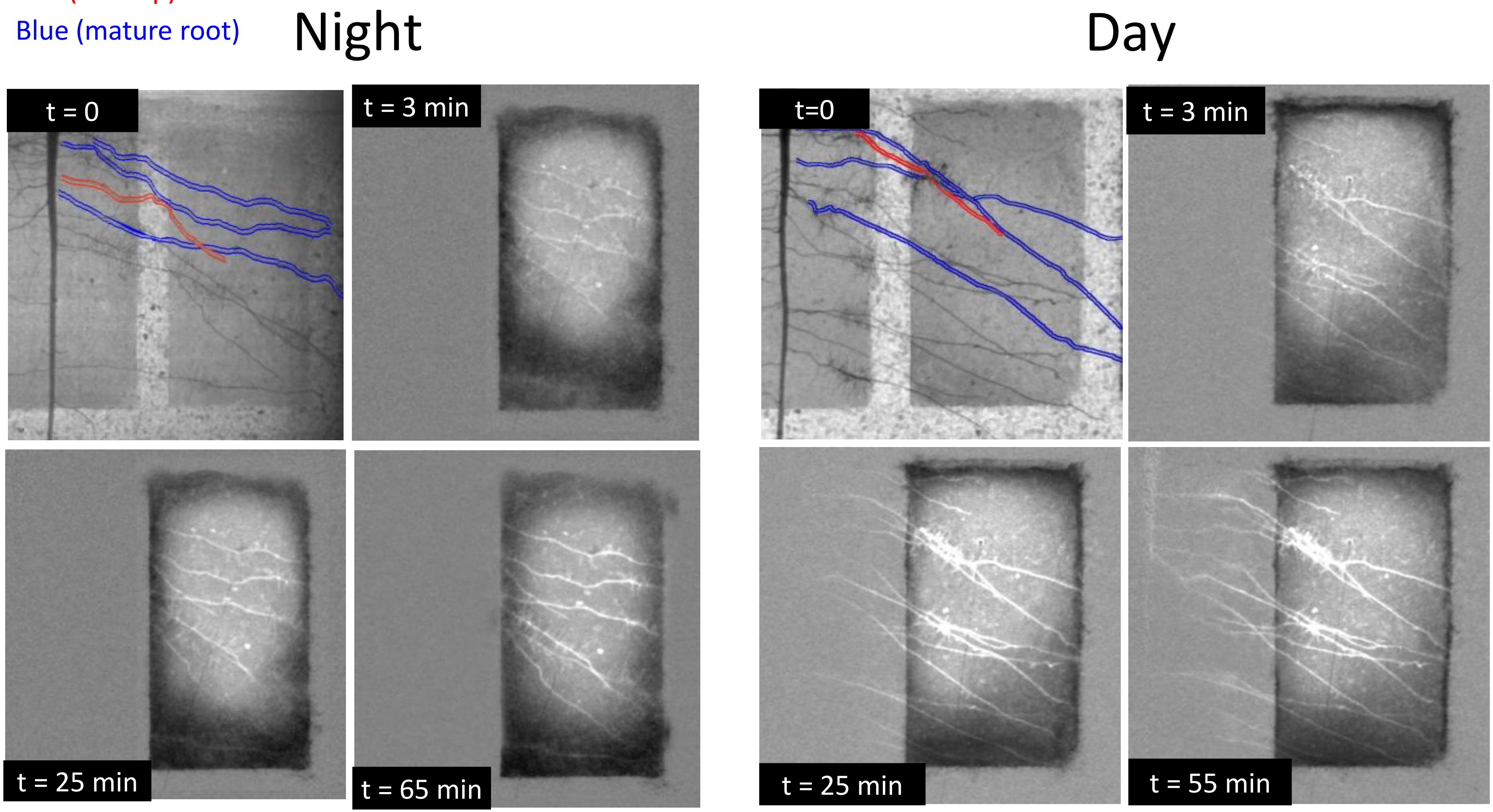


8 cm

# Injection of $D_2O$ at night and day

Zare et al. (submitted)

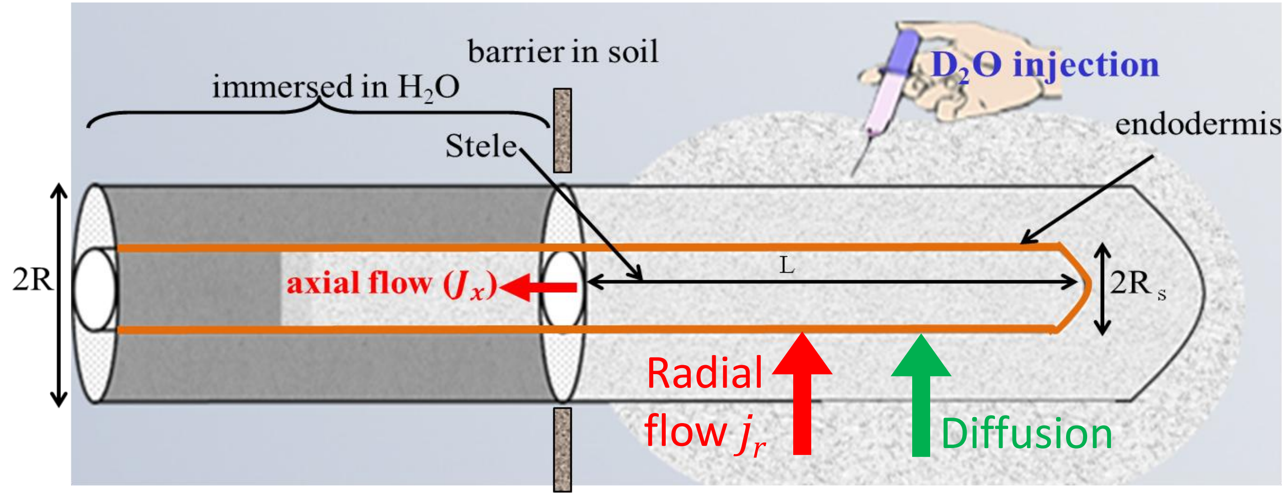
Red (root tip)
Blue (mature root)




- D2O transport into root is faster at day than at night (radial flow)
- No transport along root during night (axial flow)

# Quantification of root water uptake: $j_r$ [cm s^-1]

The transport of $D_2O$ into root is a diffusion-convection process




Diffusion Convection

$$\frac{R}{2}\frac{\partial C_s}{\partial t} = P_D(C_s - C_0) + j_r(C_s - C_0)$$

$P_D$: Diffusional permeability

$j_r$: net root water uptake

$C_s$: concentration of $D_2O$ in roots

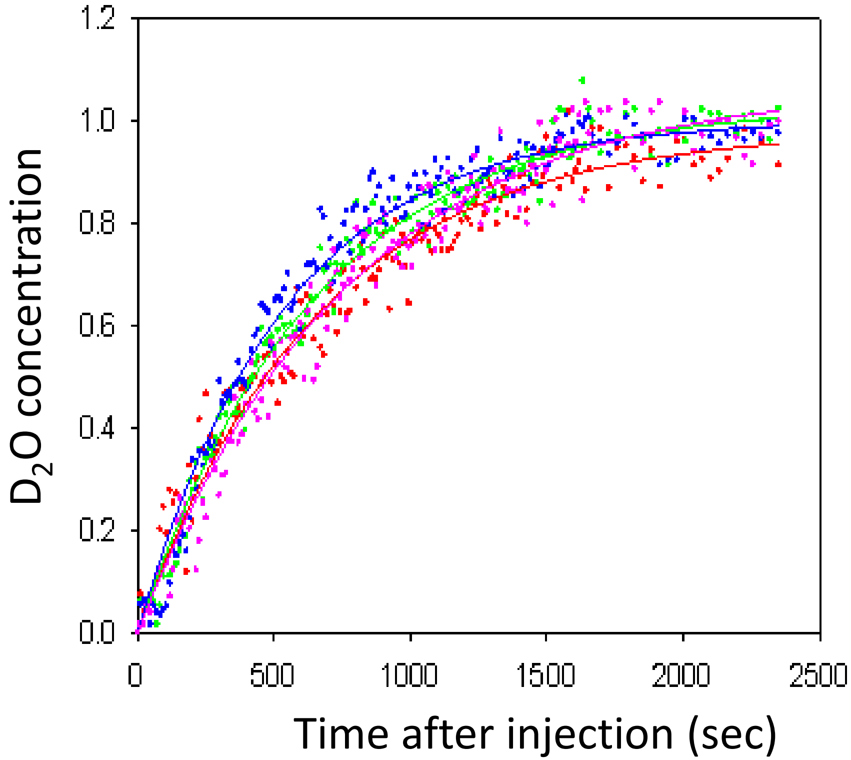
$C_0$: concentration of $D_2O$ in soil

$R$: radius of stele

Assumption:
$D_2O$ concentration in roots is uniform

# Quantification of root water uptake: $j_r$ [cm s$^{-1}$]

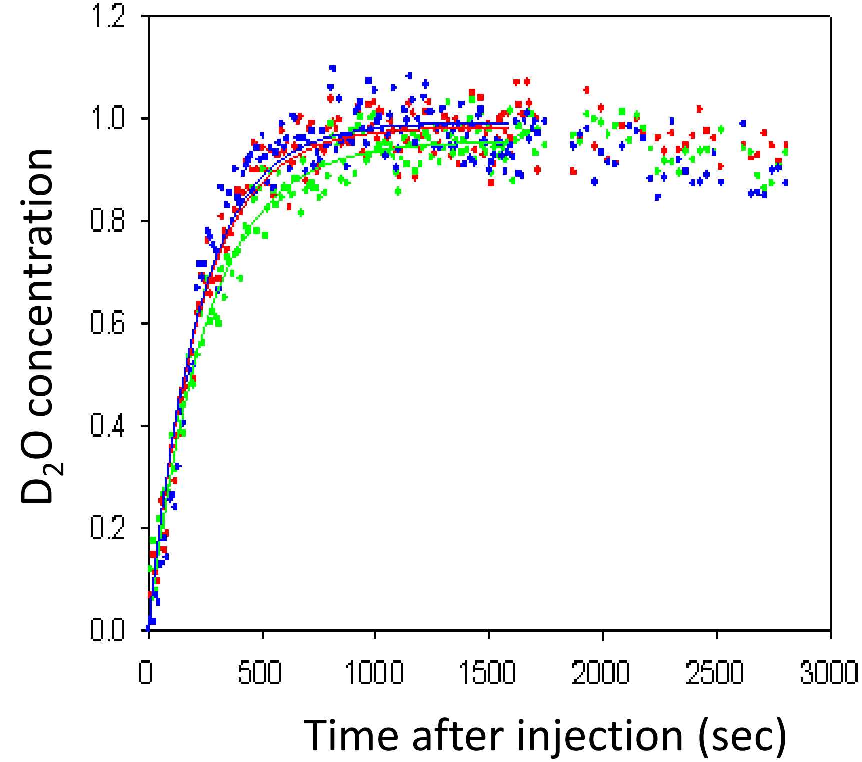
Night




$$C_s = C_0\left(1 - e^{-2\frac{P_D}{r}t}\right)$$

$P_D$ = 8.9 10$^{-6}$ cm s$^{-1}$

Day



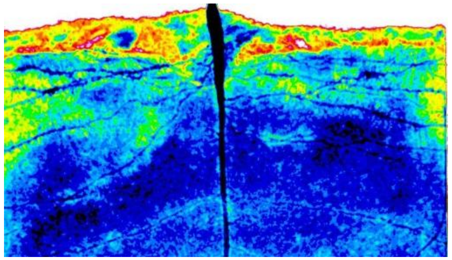

$$C_s = C_0\left(1 - e^{-2\frac{P_D + j_r}{r}t}\right)$$

$j_r$ = 1.63 10$^{-5}$ cm s$^{-1}$

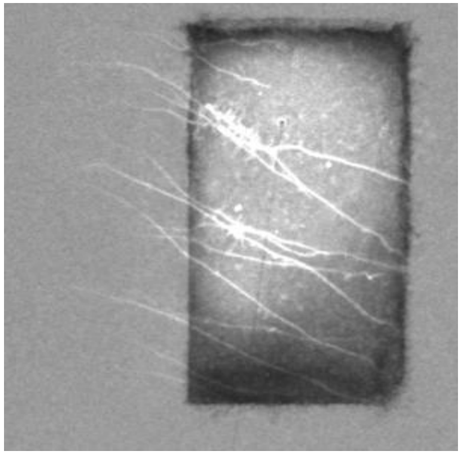
Validated with fluxes behind barrier

# Conclusions

Unexpected behaviour of the soil near the roots (~mm). The rhizosphere has distinct hydraulic properties compared to the bulk soil



Development of a new method to quantify water flow from soil to roots. We can quantitatively image how water flows inside roots



# Outlooks

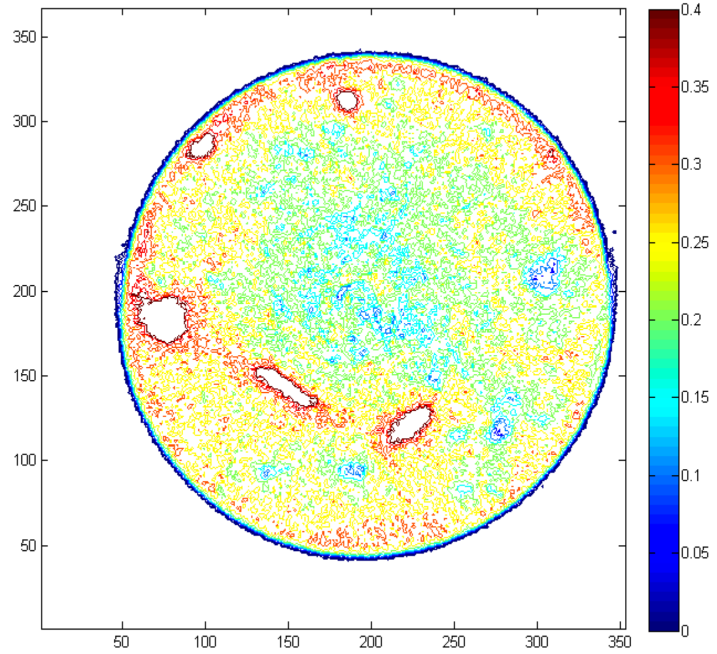
These results were possible only thanks to neutron imaging.
The „feeling“ that rhizosphere was wetter than the rest of the soil has been reported since 1939. Now we quantified it.

## How to continue?

1. To prove this theory: Better resolution to avoid artefacts – i.e. root hairs. Down to µm?

2. Image fluxes in 3D: quick tomography in ~min

2.7 cm




*Moradi et al, New Phytologist 2011*

# Acknowledgments

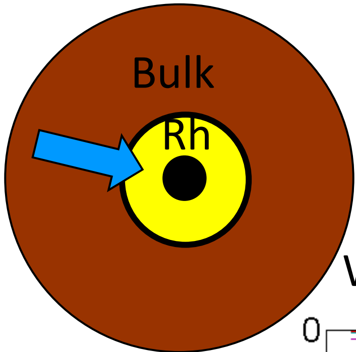
M. Zarebanadkouki and Y. Kim, Soil Hydrology, Uni-Goettingen

P. Vontobel, A. Kaestner, E. Lehmann and the imaging team at NEUTRA and ICON, Paul Scherrer Institute

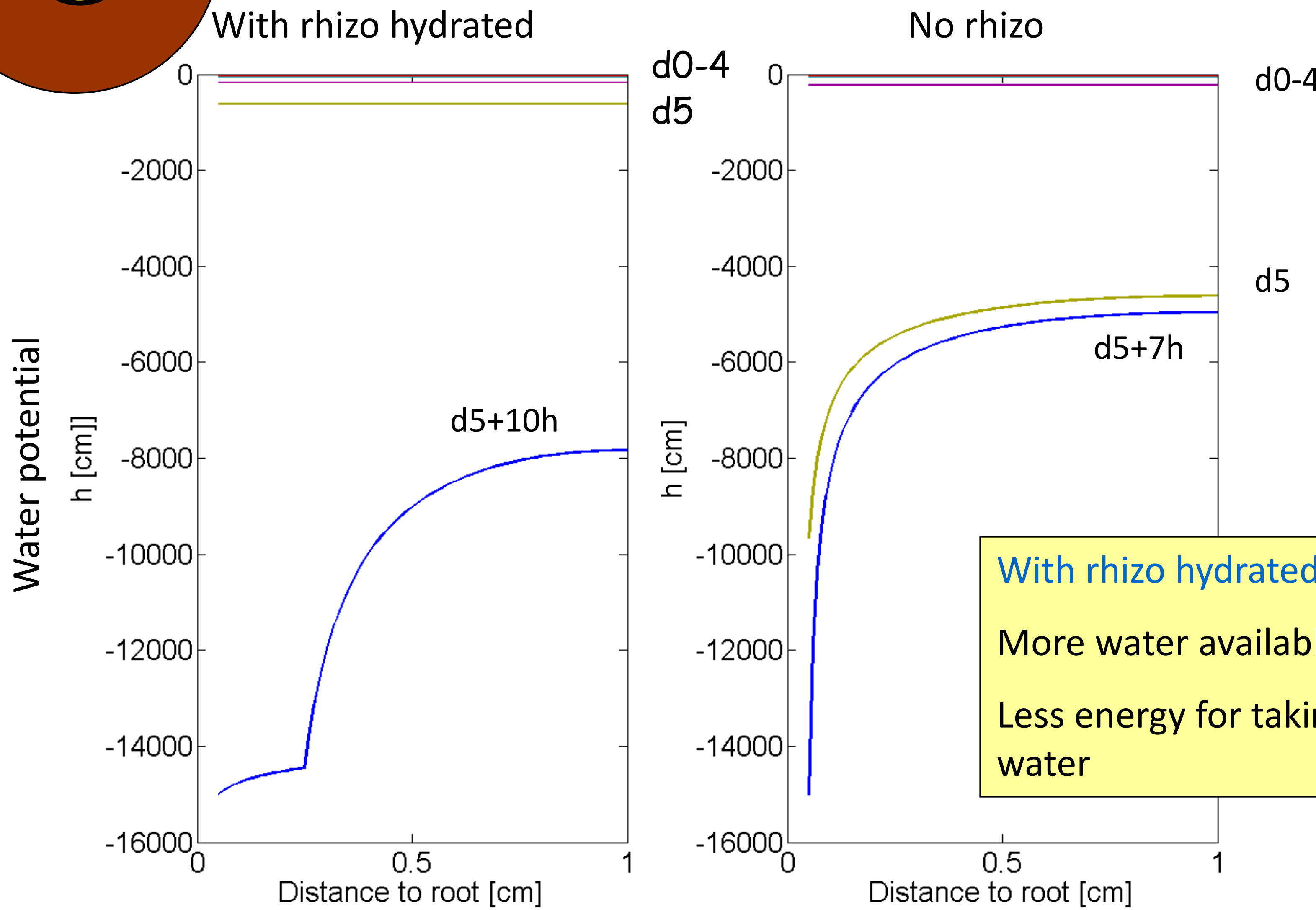
A. Moradi (UC-Davic) and S. Oswald (Uni Potsdam)

N. Kardjilov for introducing us to the use of D2O in plants

# Effects on root water uptake




*Carminati et al Vadose Zone J 2011*




With rhizo hydrated:

More water available

Less energy for taking up water

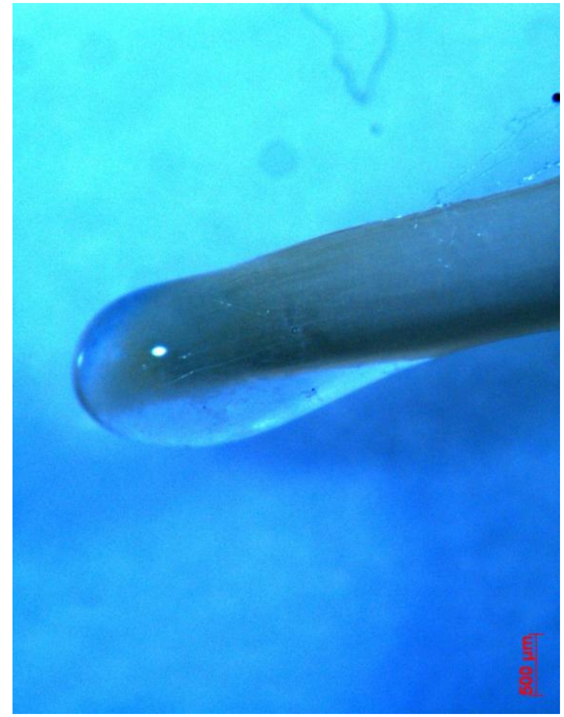
# Mucilage around roots

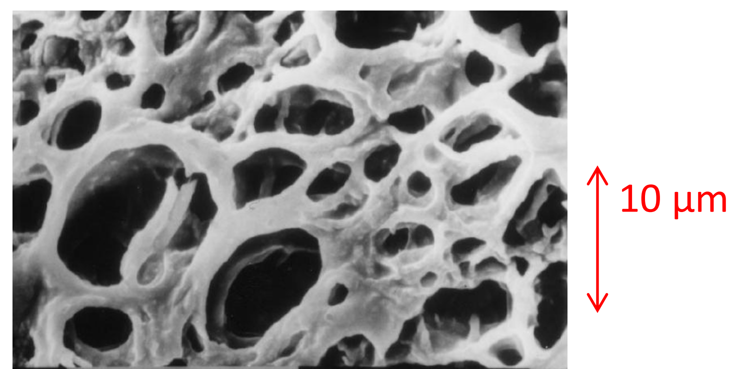
Mucilage is a thick, gluey substance produced by most plants and some microorganisms.

It is supposed to help see germination, root growth in dry soils, and to keep roots wet.

It is composed of:

- polysaccharides, like polygalacturonic acid (PGA). In presence of Ca2+ (divalent calcium) PGA may form a gel Ca-PGA
- phospholipids. Small amounts. They act as surfactants lowering the surface tension of water (Read et al., New Phyto. 2003)




Mimmo et al, Biopolymers, 2003

# Surface tension of mucilage and hydrophobicity
# Effect of phospholipids

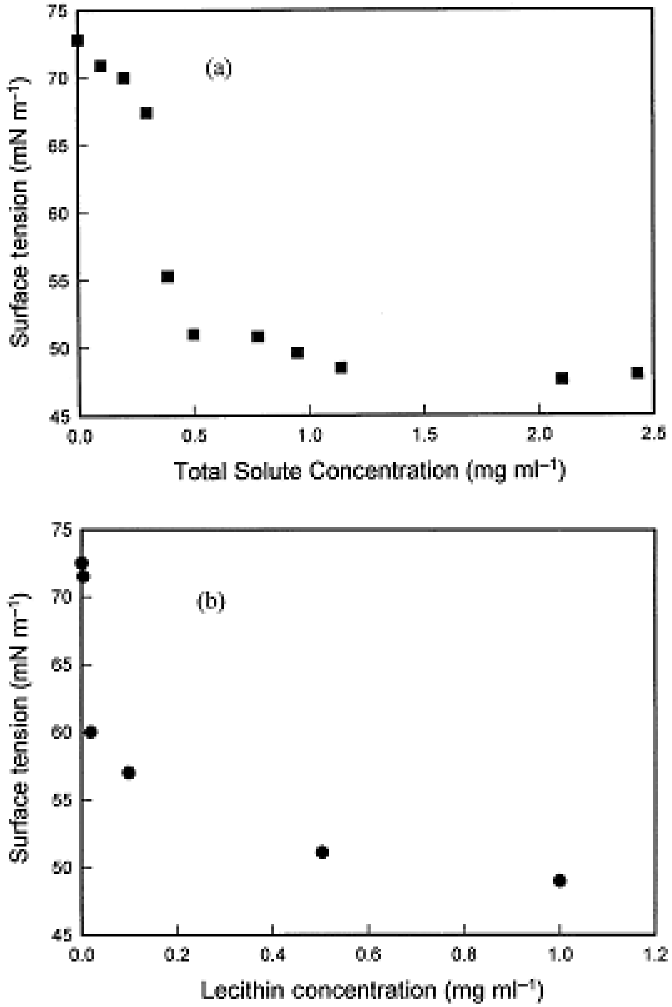



**Fig. 3** Variation of surface tension (at 20°C) of (a) filtered wheat mucilage, and (b) soybean lecithin (a phosphatidylcholine), in aqueous solution.

Read et al., New Phyto, 2003

Hydrophobicity of the rhizosphere after drying

Contact angle next to roots: 127°

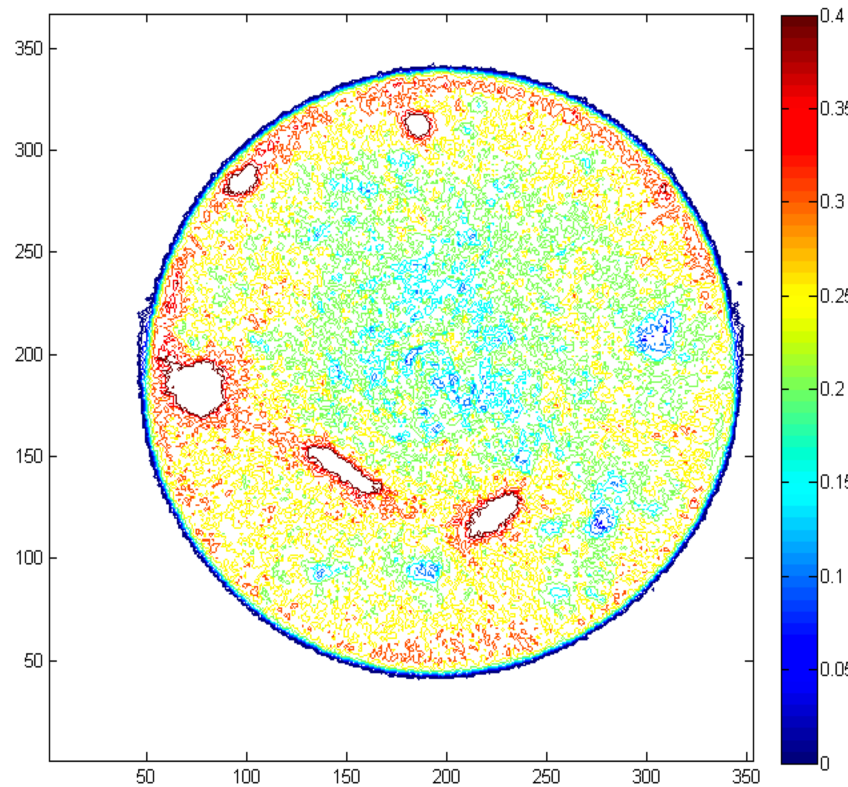
Phospolipids may cause hydrophobicity

# 3D Neutron Tomography

8 cm

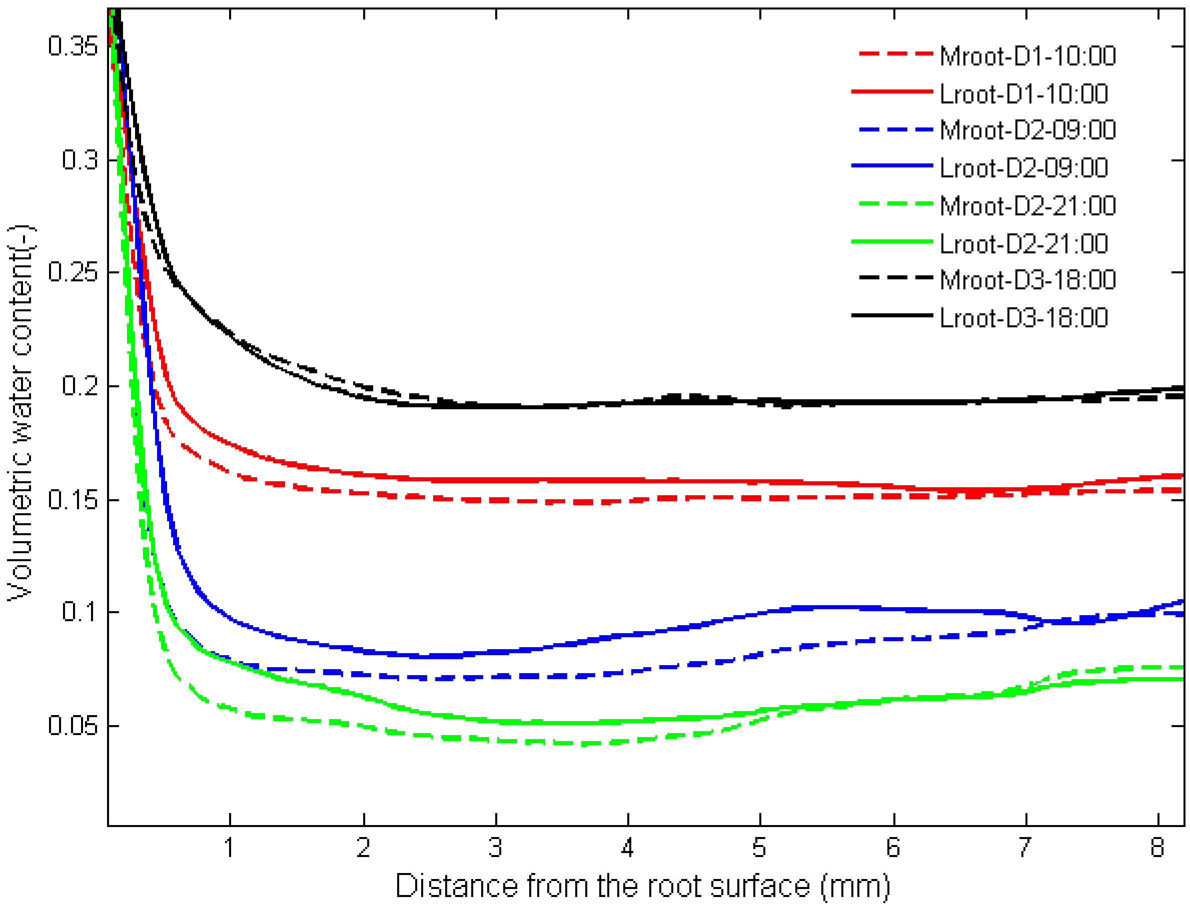
2.7 cm

Cross-section: water content around roots




*Moradi et al, New Phytologist 2011*

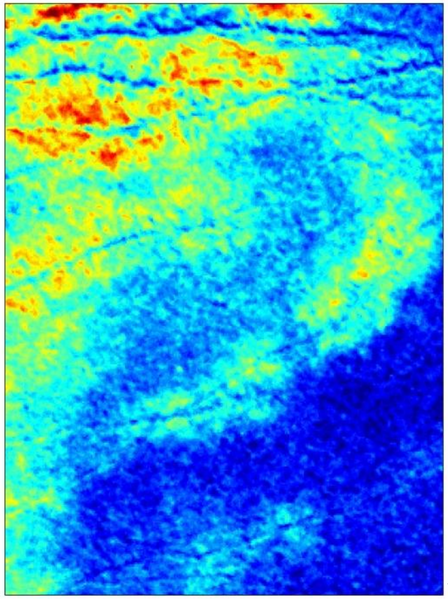
# Water content profiles towards roots



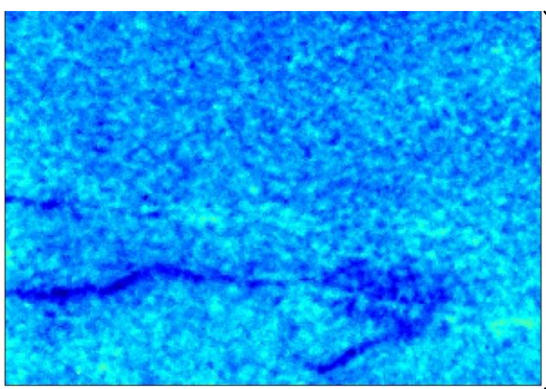

Higher water content next to roots

# Hydrophobicity varies along roots

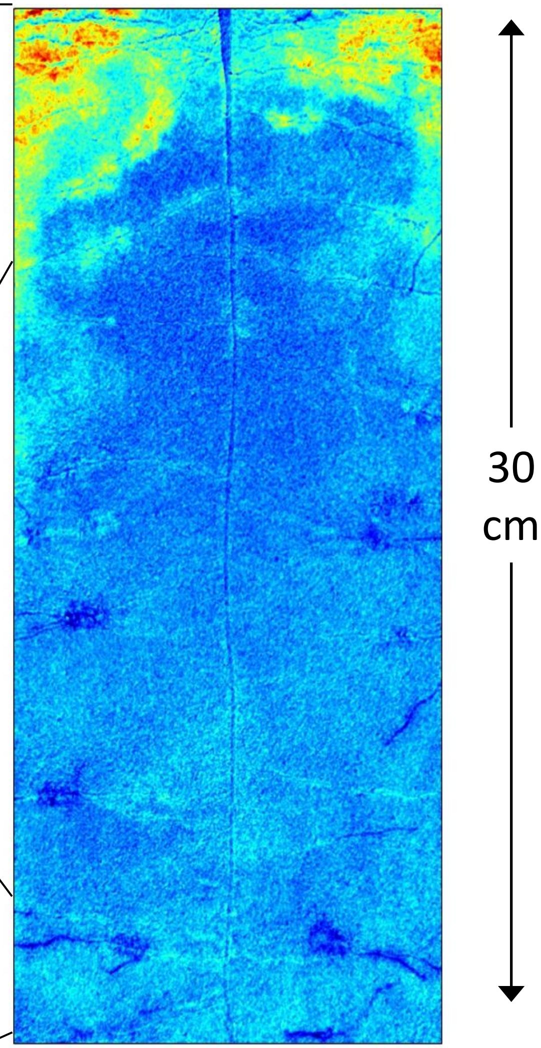
Rhizo is hydrophobic in top soil



Rhizo is wet at root tips



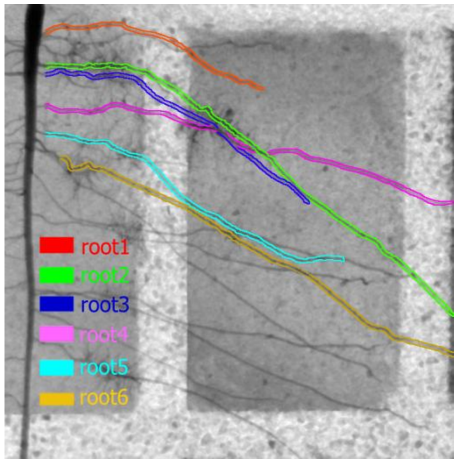
Day 5, after rewetting



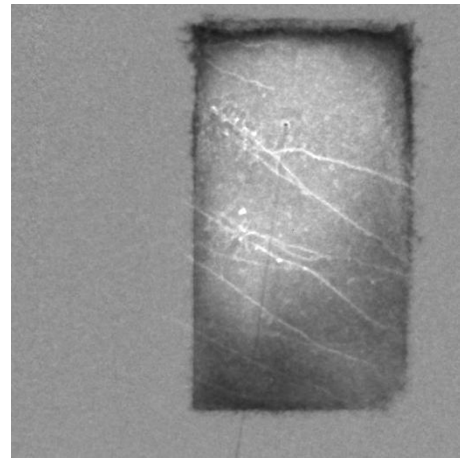

Rhizosphere becomes more hydrophobic near roots that are more active in water uptake, i.e. in dry soils.

# Imaging water fluxes in soils and roots

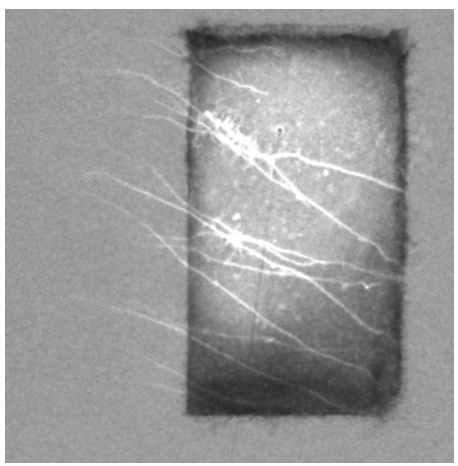
Neutron radiography of $D_2O$ transport into roots



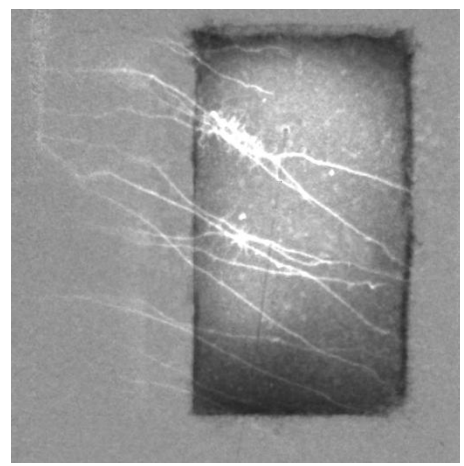

t=0 min



t=5 min



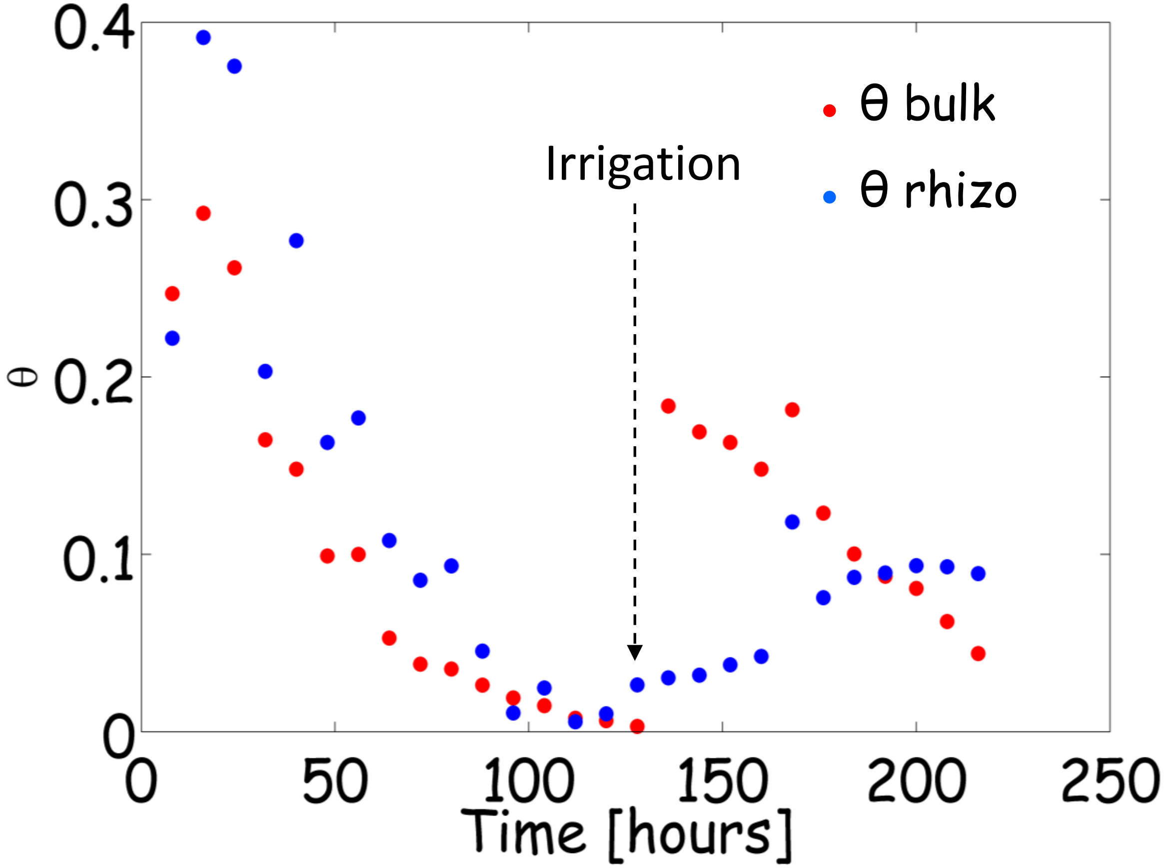
t=30 min



t=60 min

# Quantitative analysis

Average water content (bulk) and water content in the soil near roots (rhizosphere)




*Carminati et al. Plant Soil 2010*