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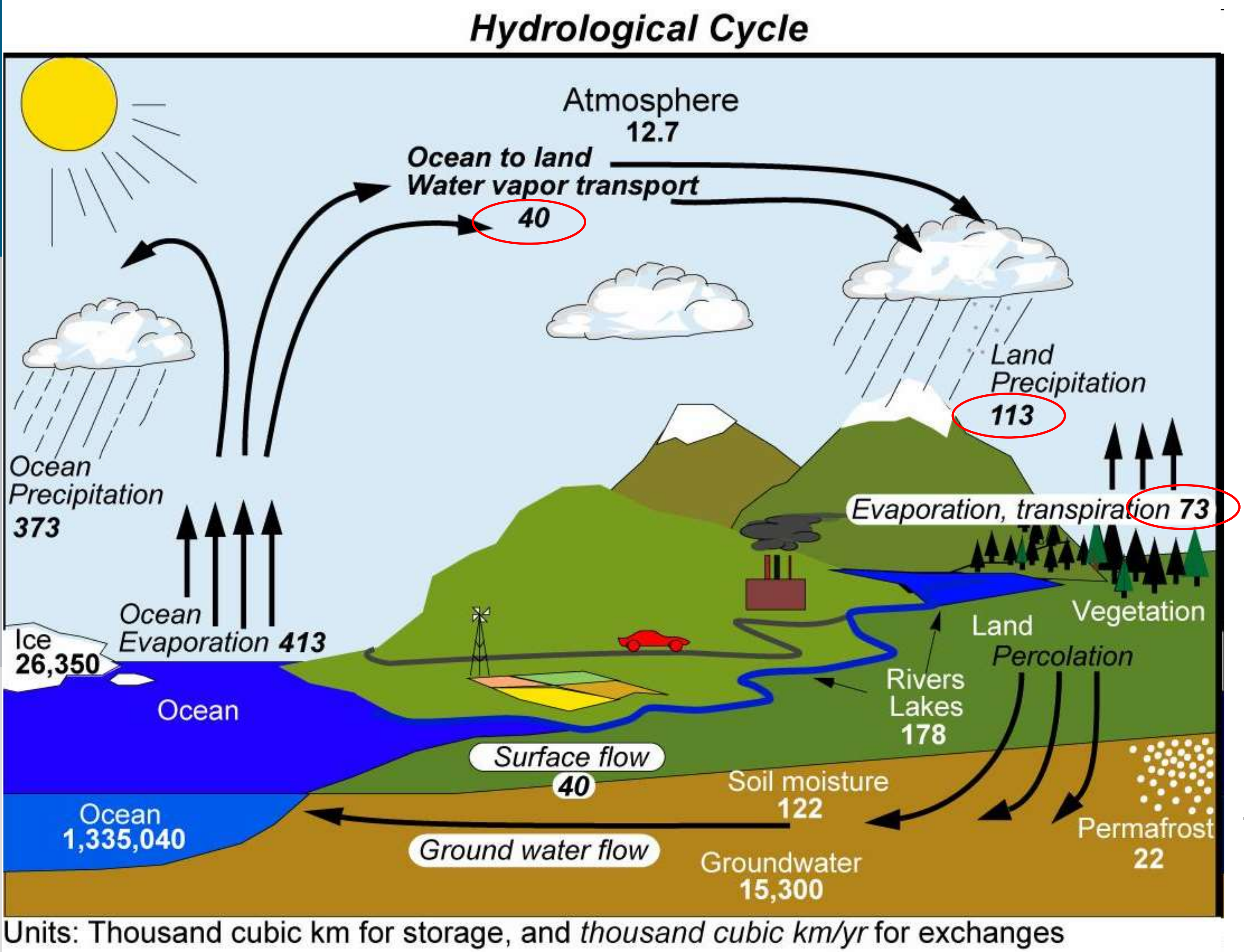
Modelling the handshaking between atmosphere and subsurface at the root-zone interface

Jan Vanderborght

Overview

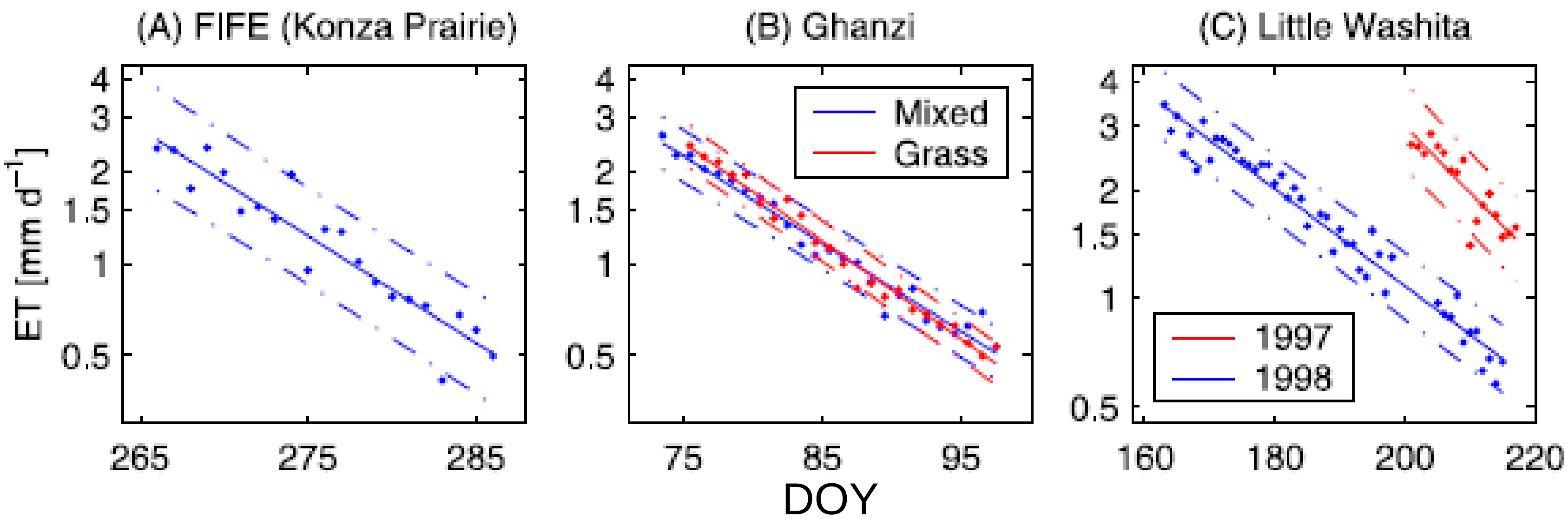
- Root water uptake in simulation models
- R-SWMS model: coupled 3-D soil-root system model
  - Effect of root architecture, root hydraulic properties
  - Water uptake from saline soils
  - Hormonal versus hydraulic regulation of transpiration
- Upscaling

Background



Trenberth et al., (2007)

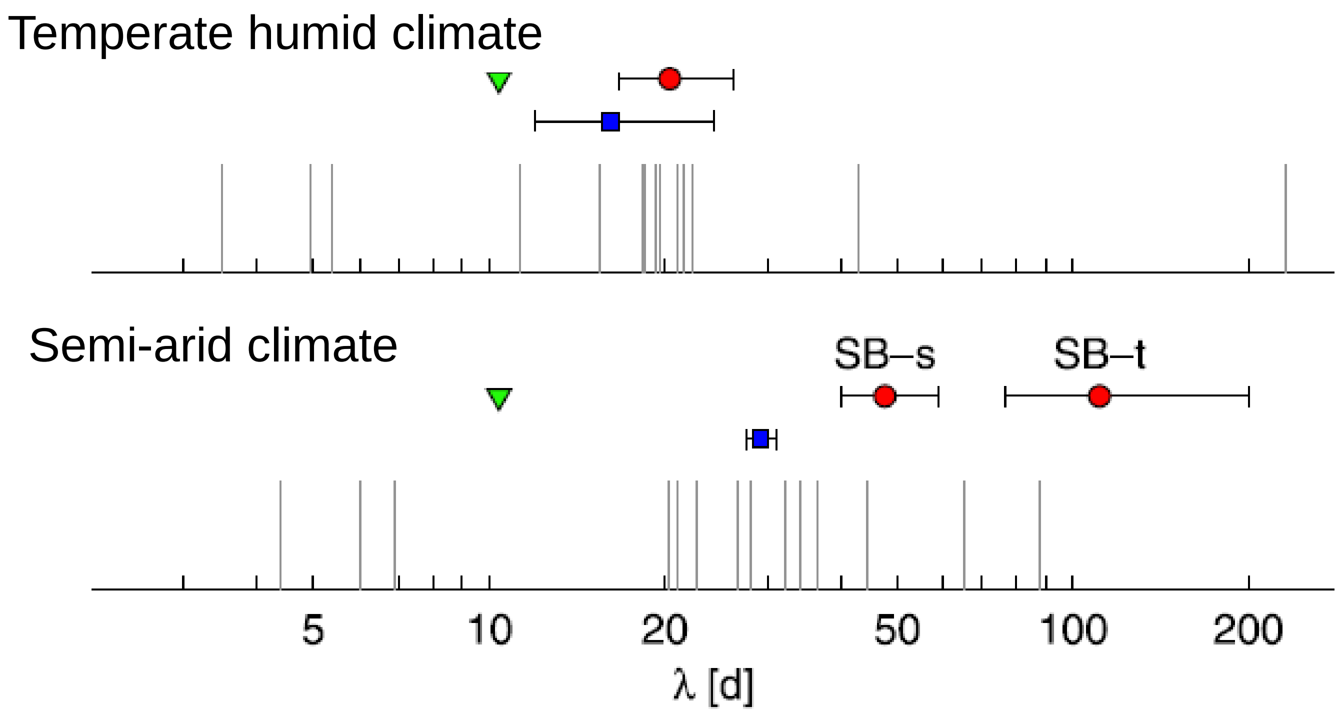
Decay of Transpiration During Dry Spells



$$ET = ET_0 exp\left[-\frac{t - t_0}{\lambda}\right]$$

Teuling et al. 2006, GRL

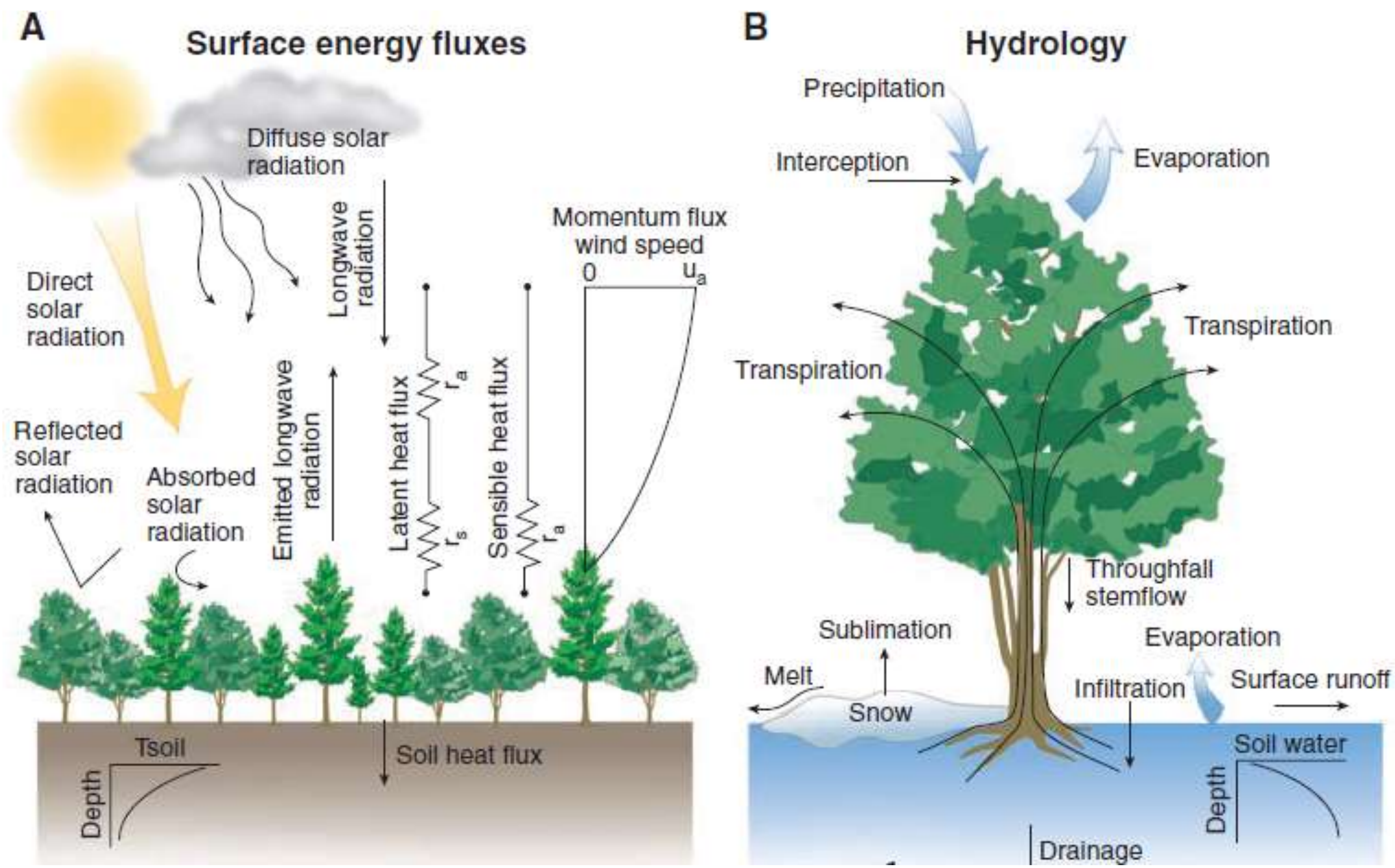
Effect of Root Water Uptake Model on Surface Water Flux



Prediction of the decrease of evaportranspiration with time by different LSMs → effect of uptake by deep roots?

Teuling et al. 2006, GRL

Representation of Land Surface-Atmosphere Interactions



Vertical scale is the scale of the canopy and soil profile: O 10^1 m

Vertical resolution: O 10^{-3} - 10^{-1} m

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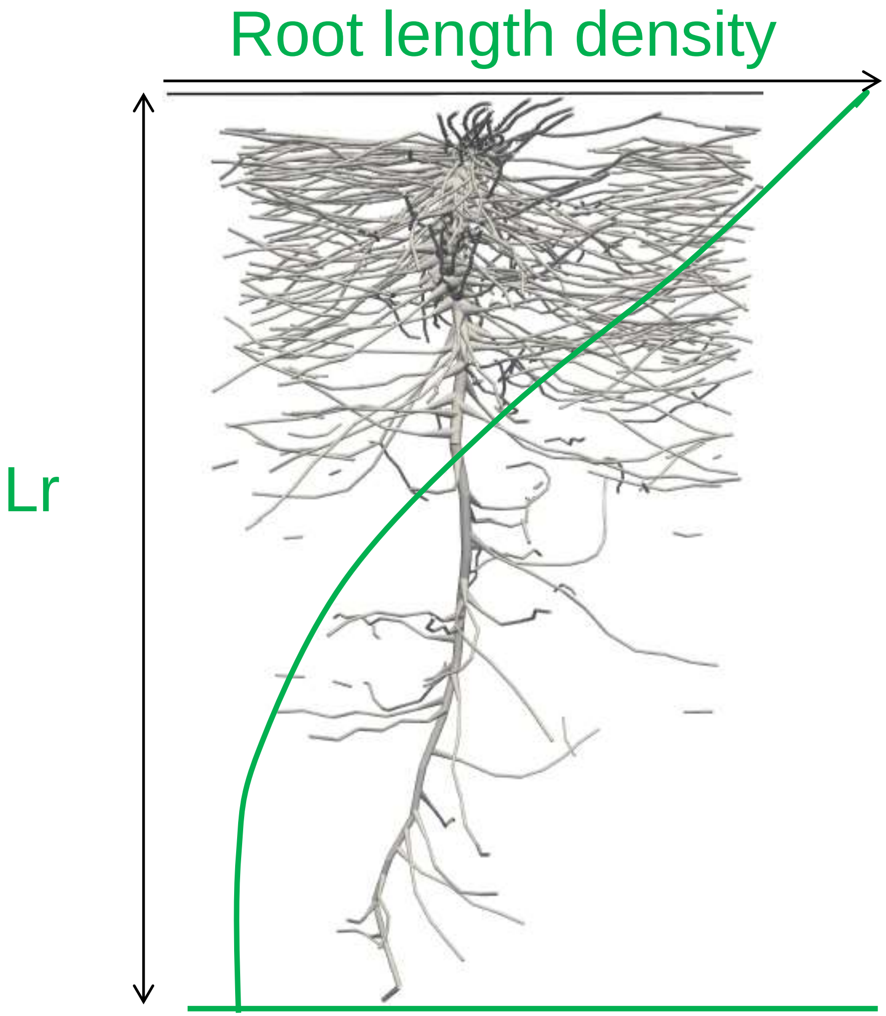
Representation of Root Water Uptake in Land Surface-Atmosphere Interactions



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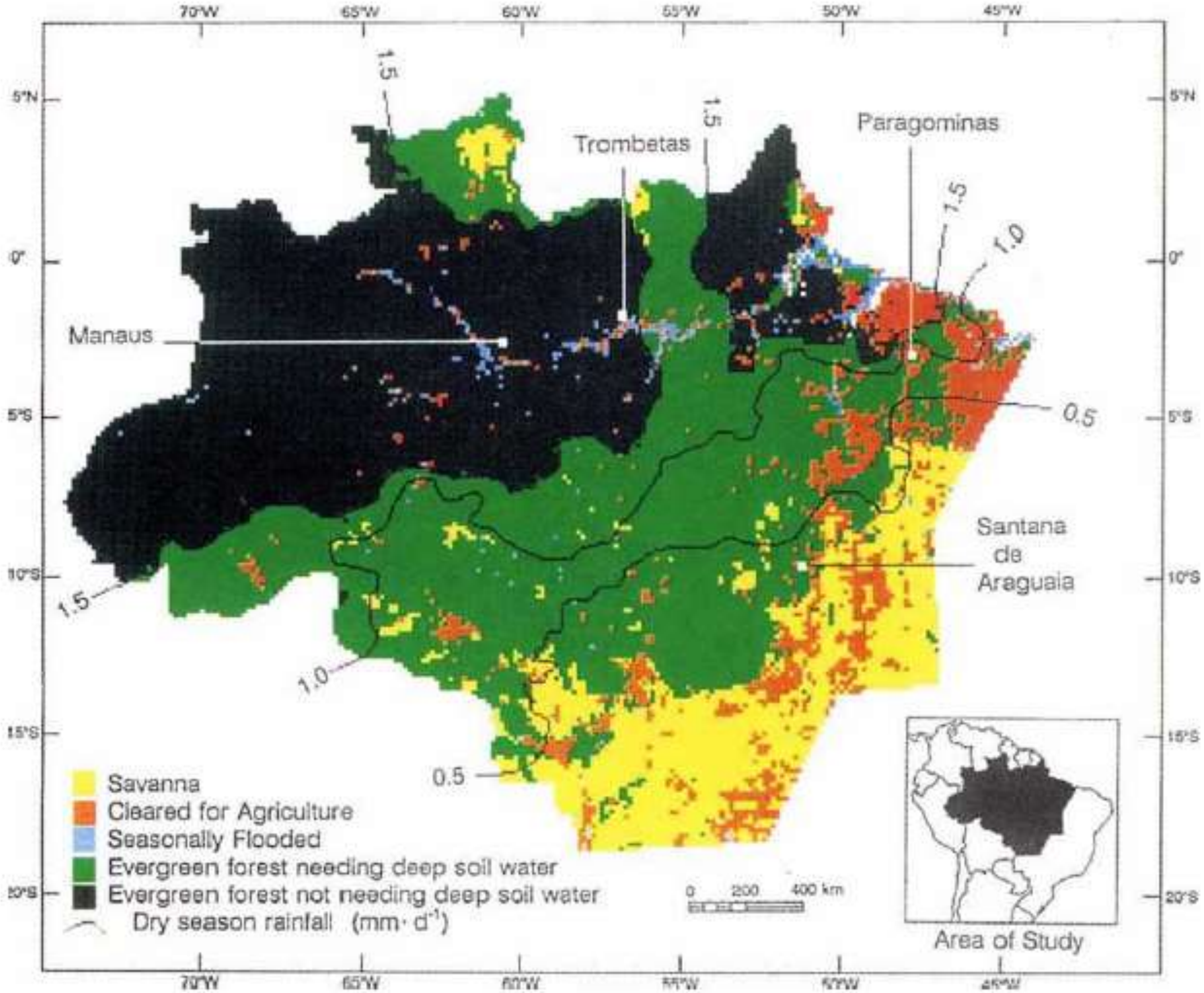
Why is there evergreen forest in regions where the dry season rainfall is below 1.5 mm d^{-1}?



Nepstad et al., Nature, 1994

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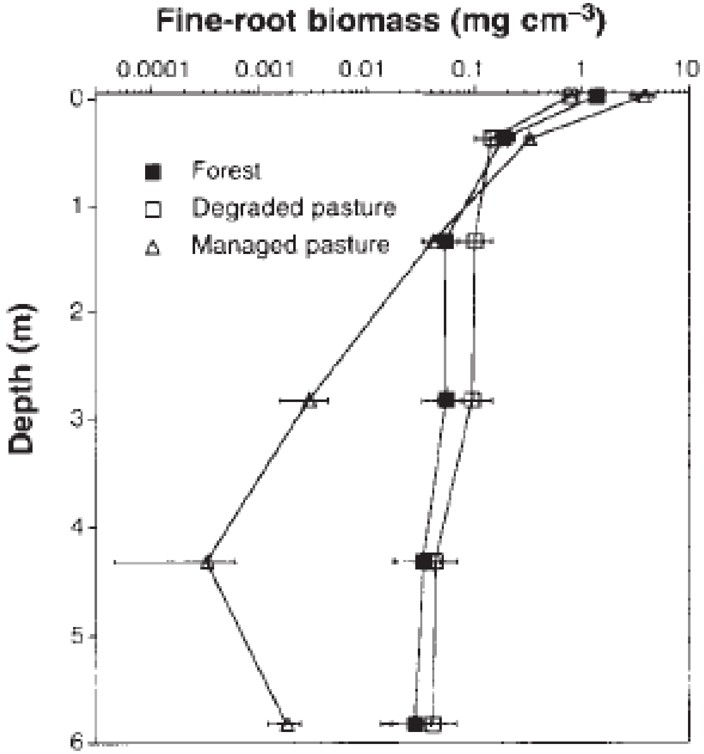
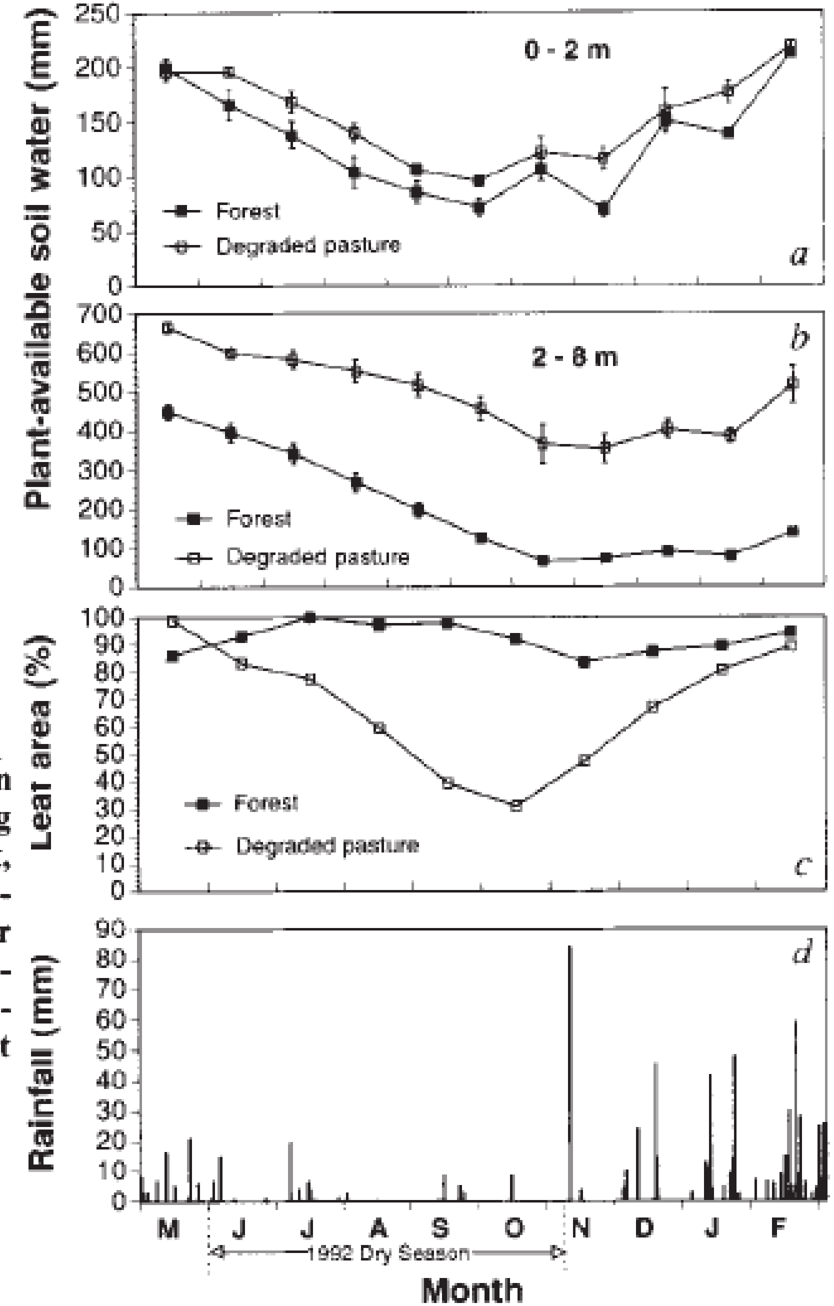
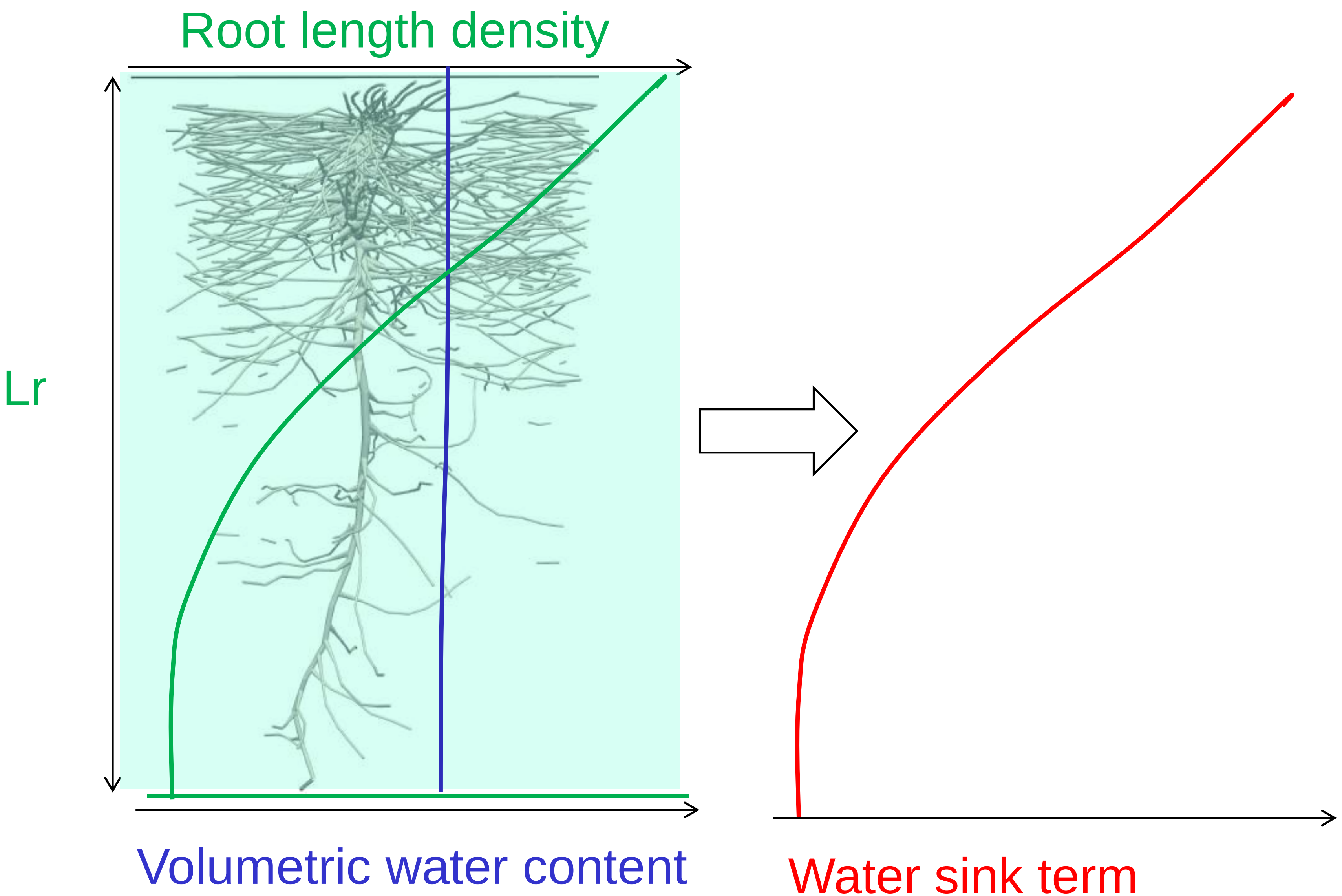




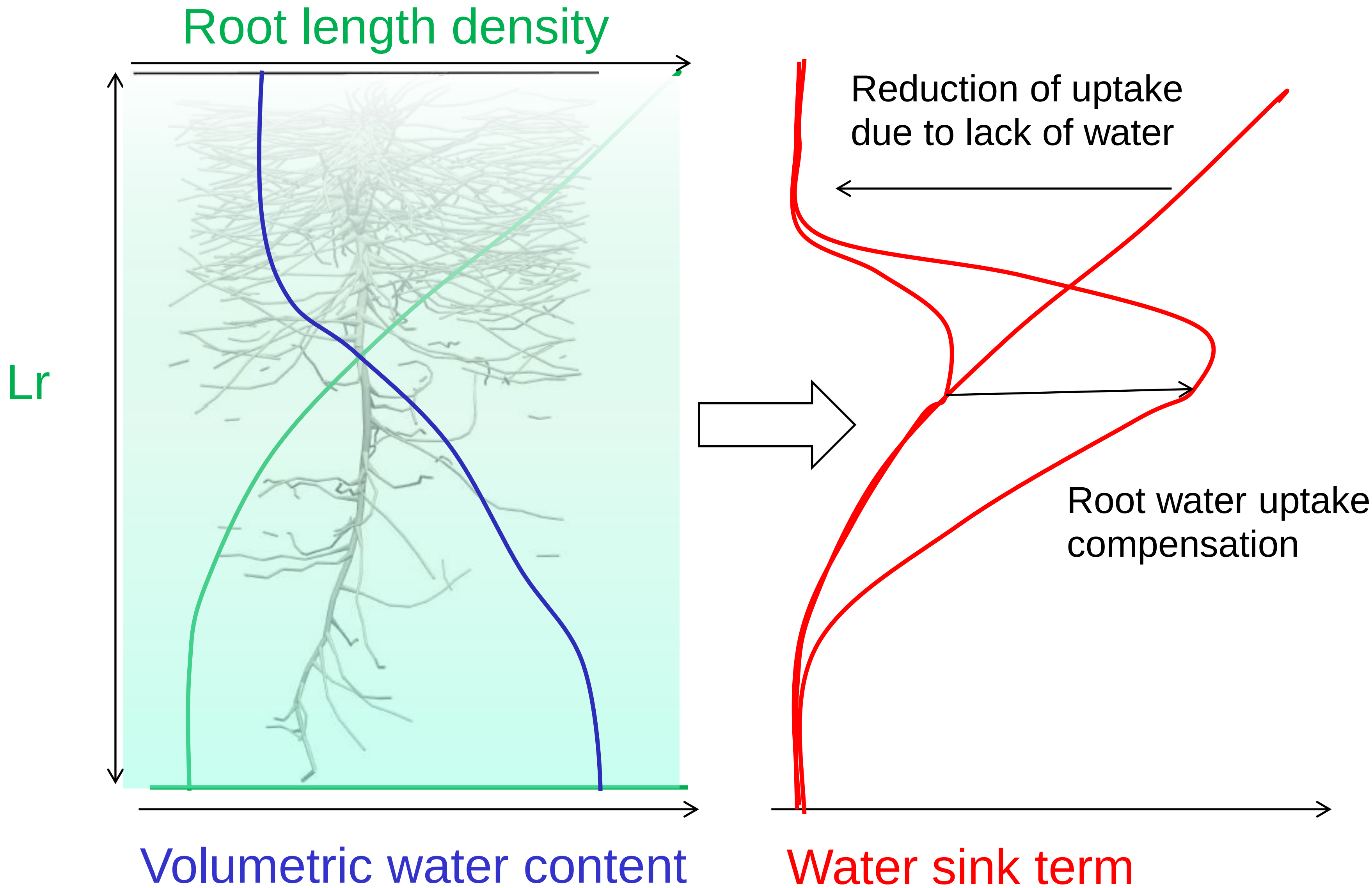
season. Evergreen forests in northeastern Pará state maintain evapotranspiration during five-month dry periods by absorbing water from the soil to depths of more than 8 m. In contrast, although the degraded pastures of this region also contain deep-rooted woody plants, most pasture plants substantially reduce their leaf canopy in response to seasonal drought, thus reducing dry-season evapotranspiration and increasing potential subsurface run-off relative to the forests they replace. Deep roots that extract

Nepstad et al., Nature, 1994

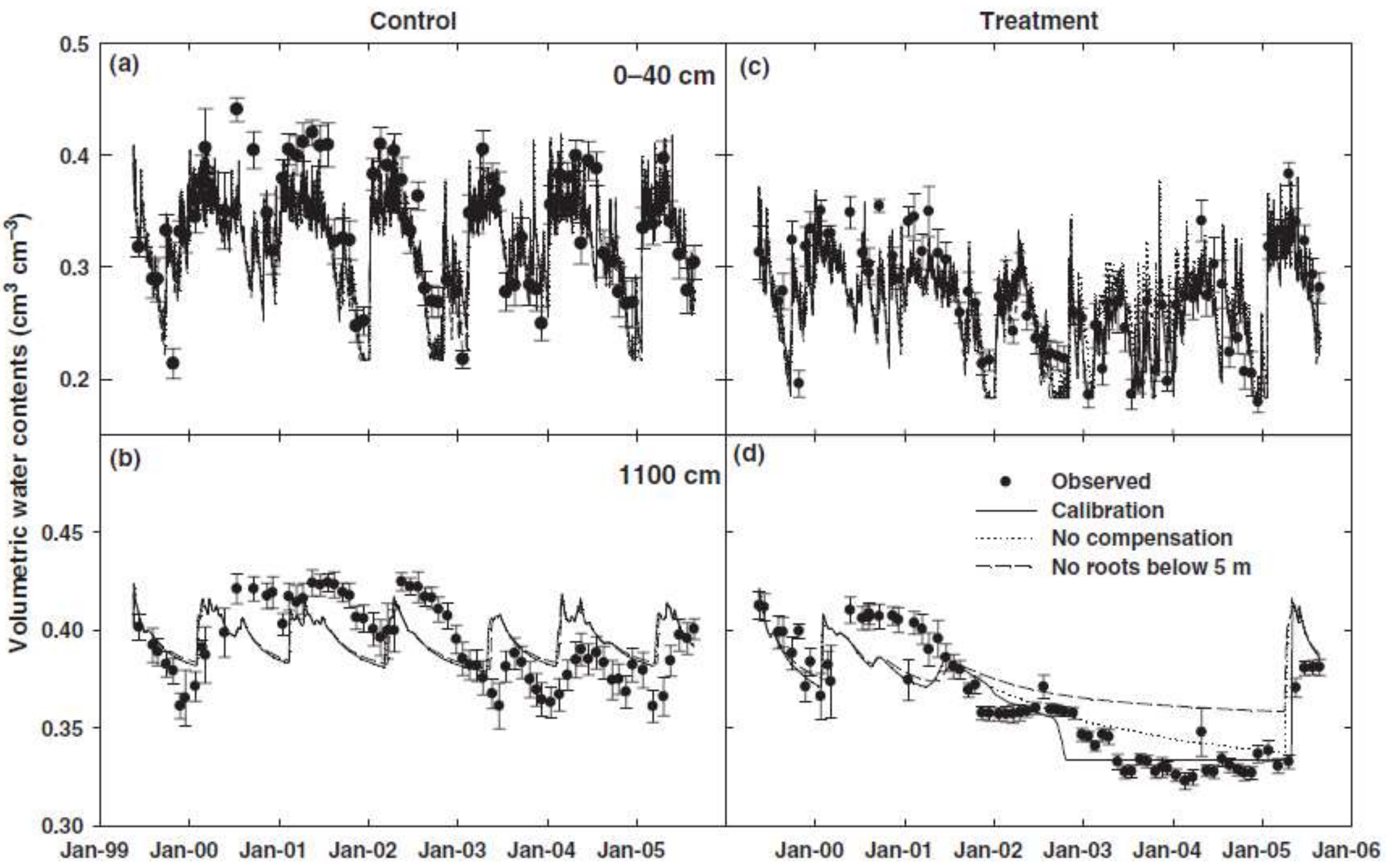
Representation of Root Water Uptake in Land Surface-Atmosphere Interactions



Representation of Root Water Uptake in Land Surface-Atmosphere Interactions

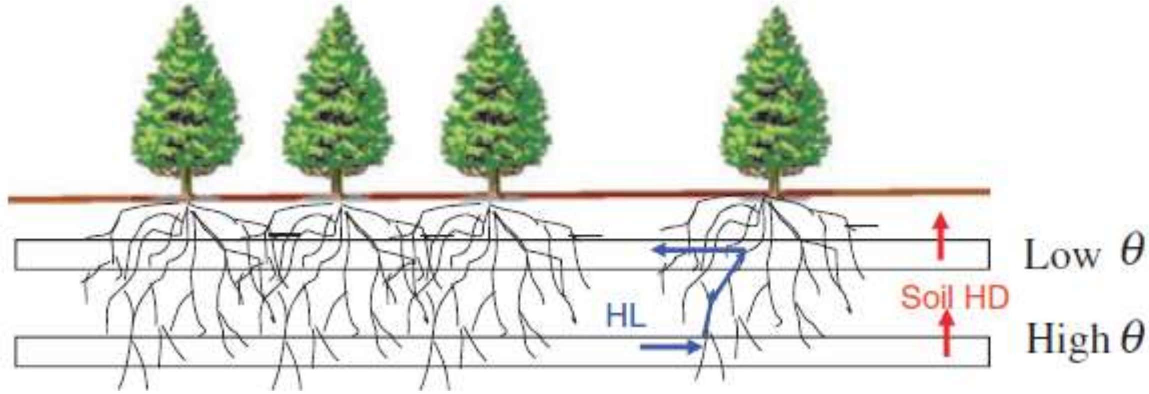


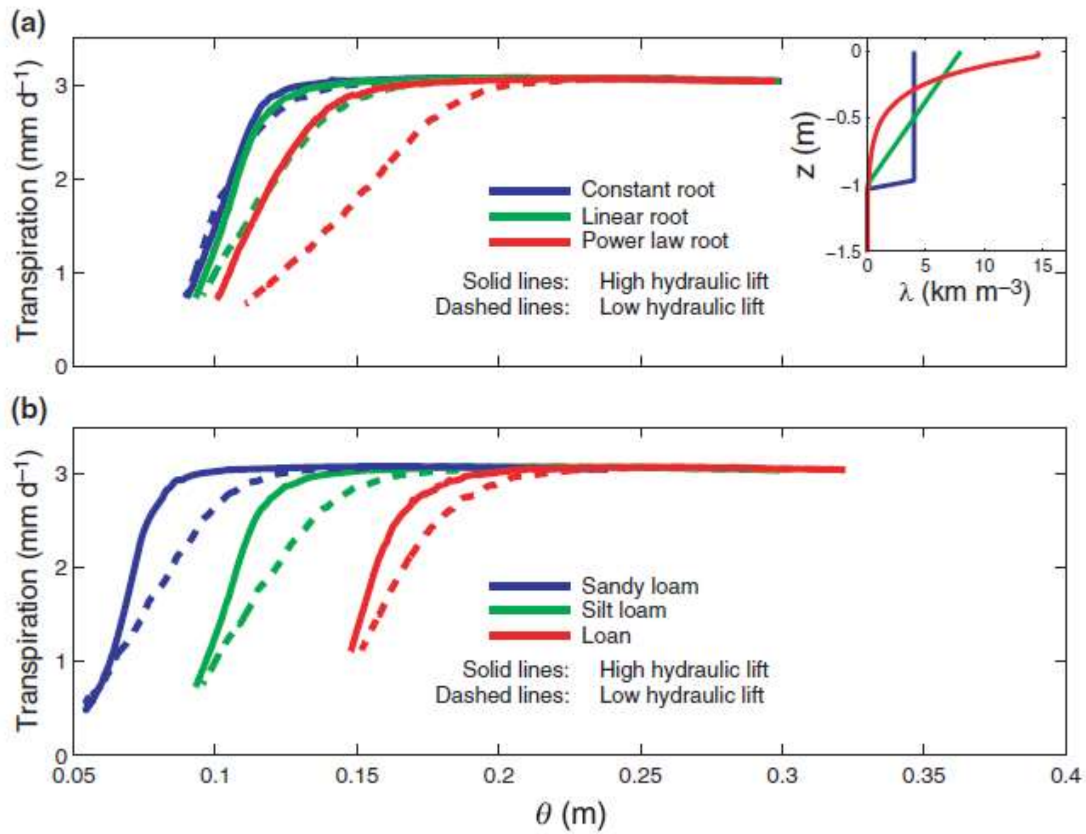
Root Water Uptake Compensation



Markewitch et al., New Phytologist, 2010

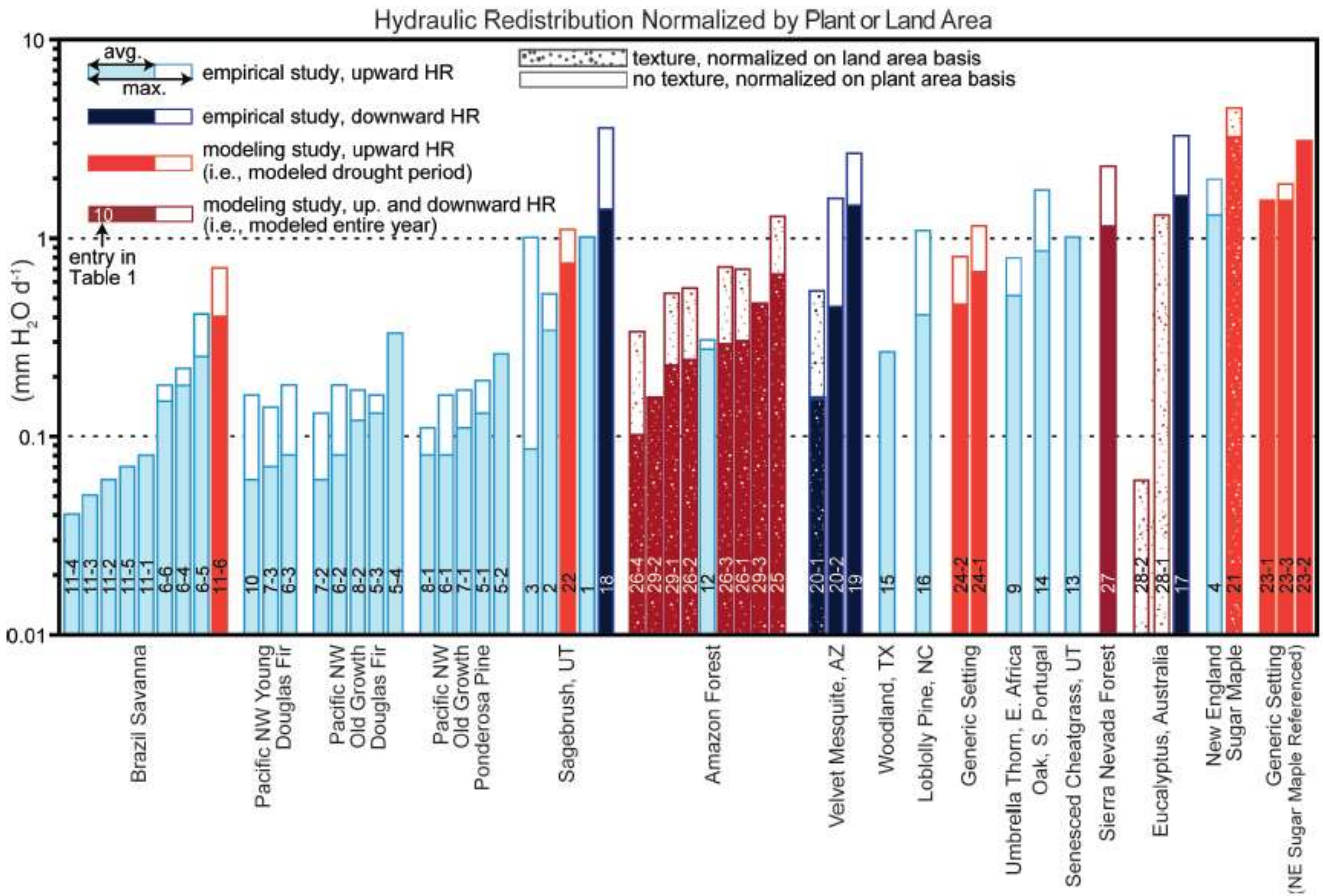
Hydraulic Lift





Katul and Siqueira, New Pythologist, 2010.

Hydraulic Redistribution/Lift



Neumann and Cardon, New Phytologist, 2012

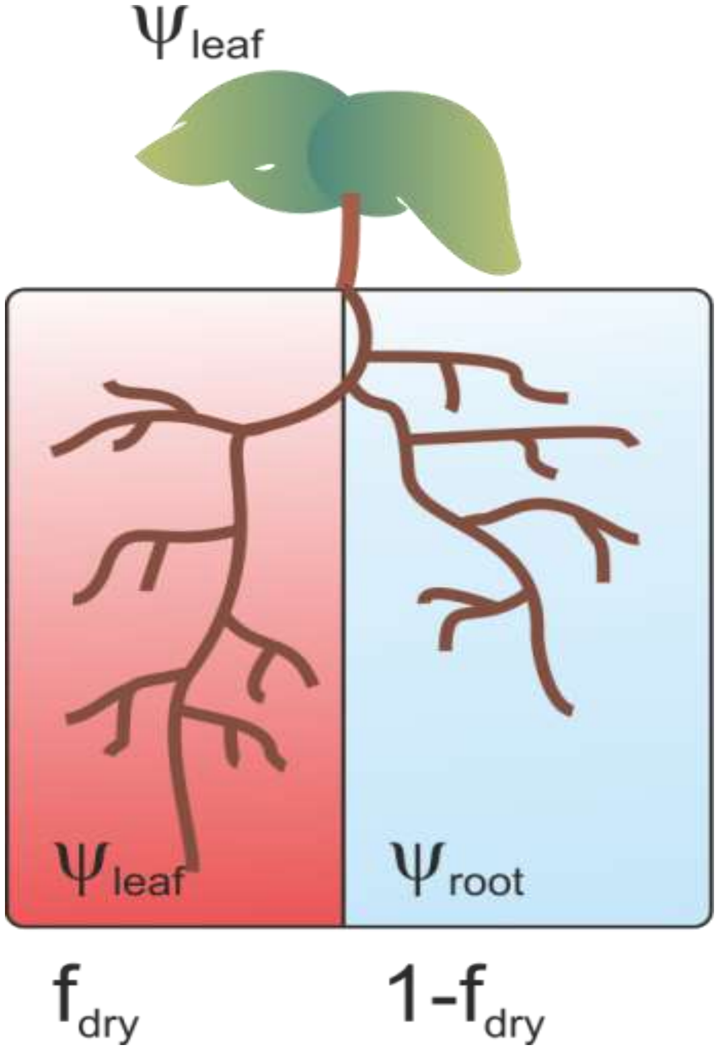
Hydraulic Redistribution/lift

Ecological functions of hydraulic lift

- increasing dry-season transpiration
- Providing water to shallow rooted plants
- Moistening upper soil layer to keep up nutrient uptake and microbiological activity
- prolonging life span of fine roots and maintaining root–soil contact in dry soils
- moving precipitation down into deeper soil layers

Partial Root Zone Drying (PRD)

Effect of heterogeneous water distributions in horticulture, orchards.



RWU in Vadose Zone Hydrological Models

Soil-based approach: sink-term, S(z,t), with simplified assumptions regarding RWU

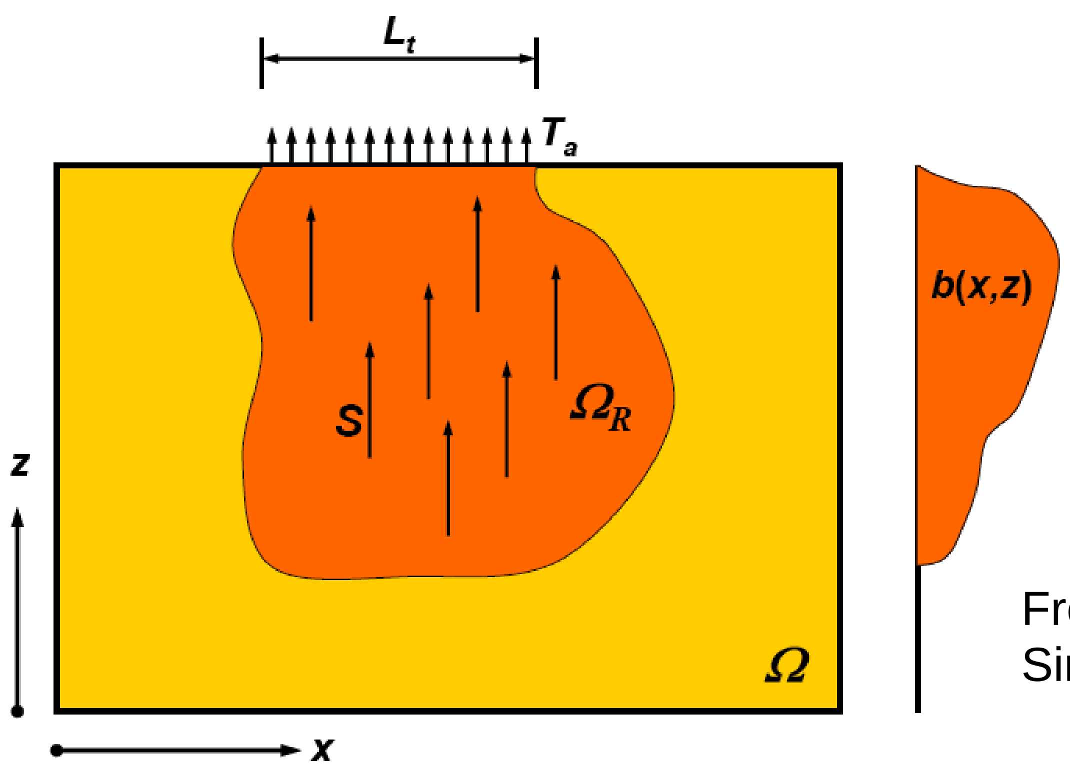
$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi_s)\frac{\partial \psi_s}{\partial z}\right] - S(z,t)$$

Several properties or characteristics of root systems are not represented or considered

RWU in Vadose Zone Hydrological Models

S is proportional to the root length density

$$S(\mathbf{x}) = T_p \frac{RLD(\mathbf{x})}{\int_{\Omega_R} RLD(\mathbf{x}) d\mathbf{x}} = T_p b(\mathbf{x})$$

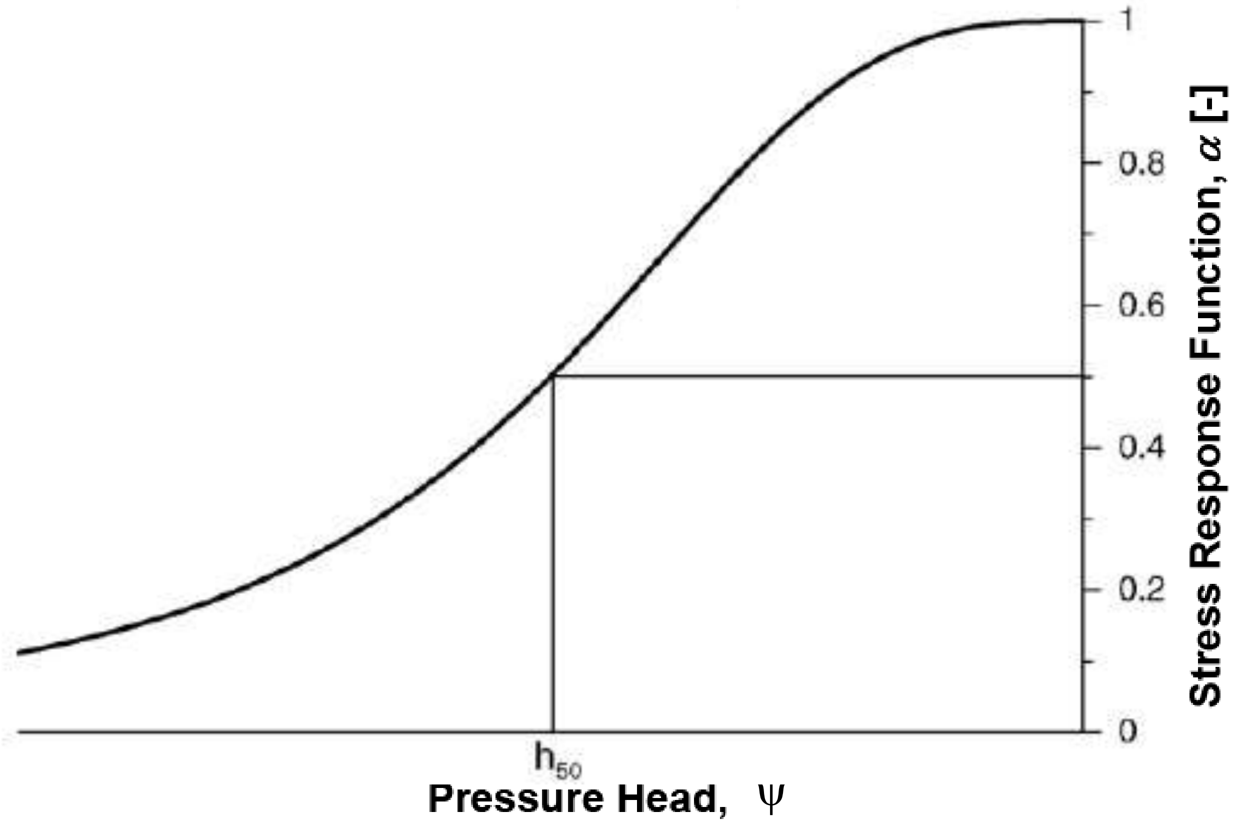


From Hydrus manuals
Simunek et al.

RWU in Vadose Zone Hydrological Models

Stress response functions are used to account for water stress on RWU:

$$S(\mathbf{x}) = T_p b(\mathbf{x}) \alpha(\psi, T_p)$$

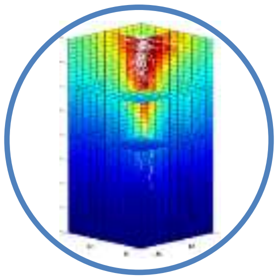


van Genuchten, 1987

R-SWMS

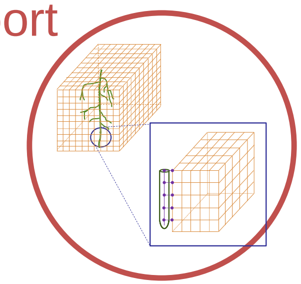
Modeling Root-Soil Water Movement and Solute transport

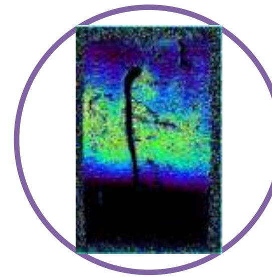
Coupled soil and root water flow



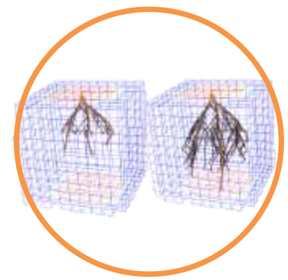
Solute transport and uptake (large scale)

Solute transport and uptake (small scale)

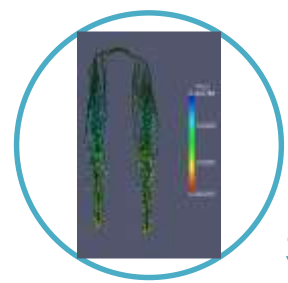




Data comparison



Root growth



Solute transport inside roots/signaling

Water Flow in a Root System (Doussan et al. 2006)

Hypotheses: osmotic gradient is negligible/ no capacity/ S-S conditions

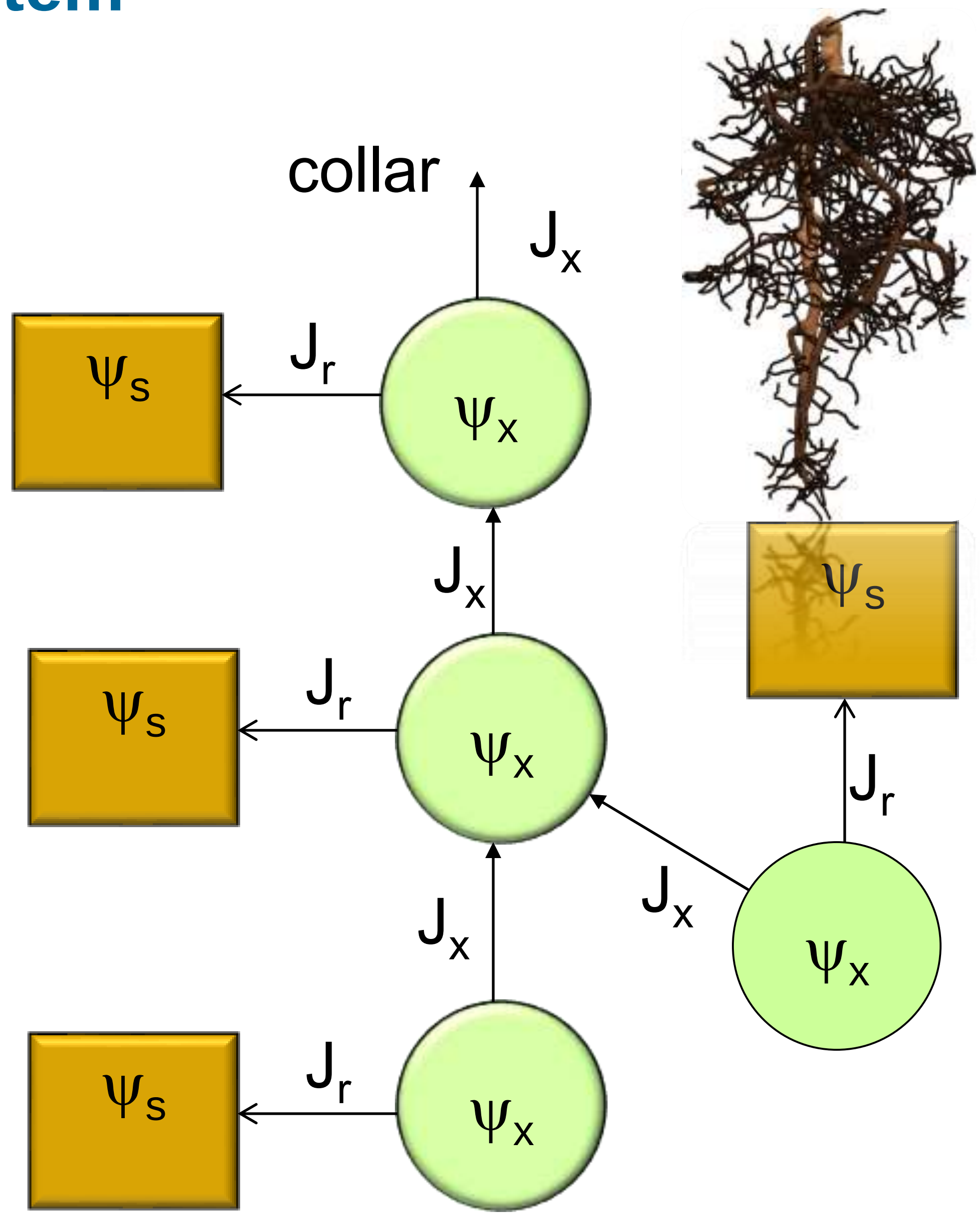
for each root node:

$$J_x = -K_x A_x \frac{\Delta \psi_x(z)}{dl_{seg}}$$

$$J_r = K_r S_r \left[\psi_s(z) - \psi_x(z)\right]$$

⇒System of equations with ψ_x as unknown

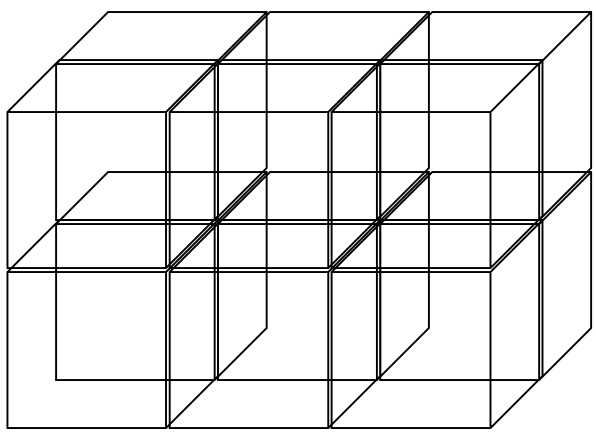
BC: $J_x(t)$ or $\psi_x(t)$ at the collar
ψ_s for each node



Coupled Water Flow Model R-SWMS (Javaux et al. 2008)

SOIL

<u>geometry</u>: grid with hexahedra subdivided in tetrahedra

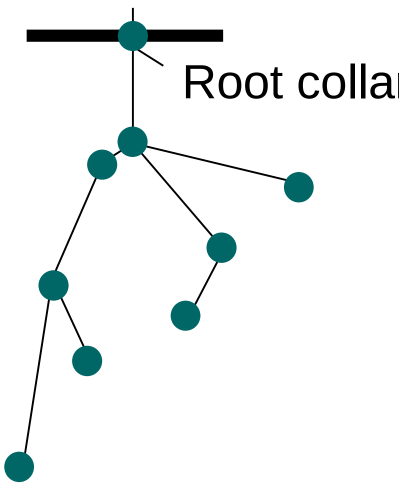


<u>numerics</u>: Richards' equation with sink term S given by the soil-root fluxes.
Based on SWMS_3D (Simunek, Huang, and van Genuchten, 1995)

$$S = \frac{\sum J_r}{V_s}$$

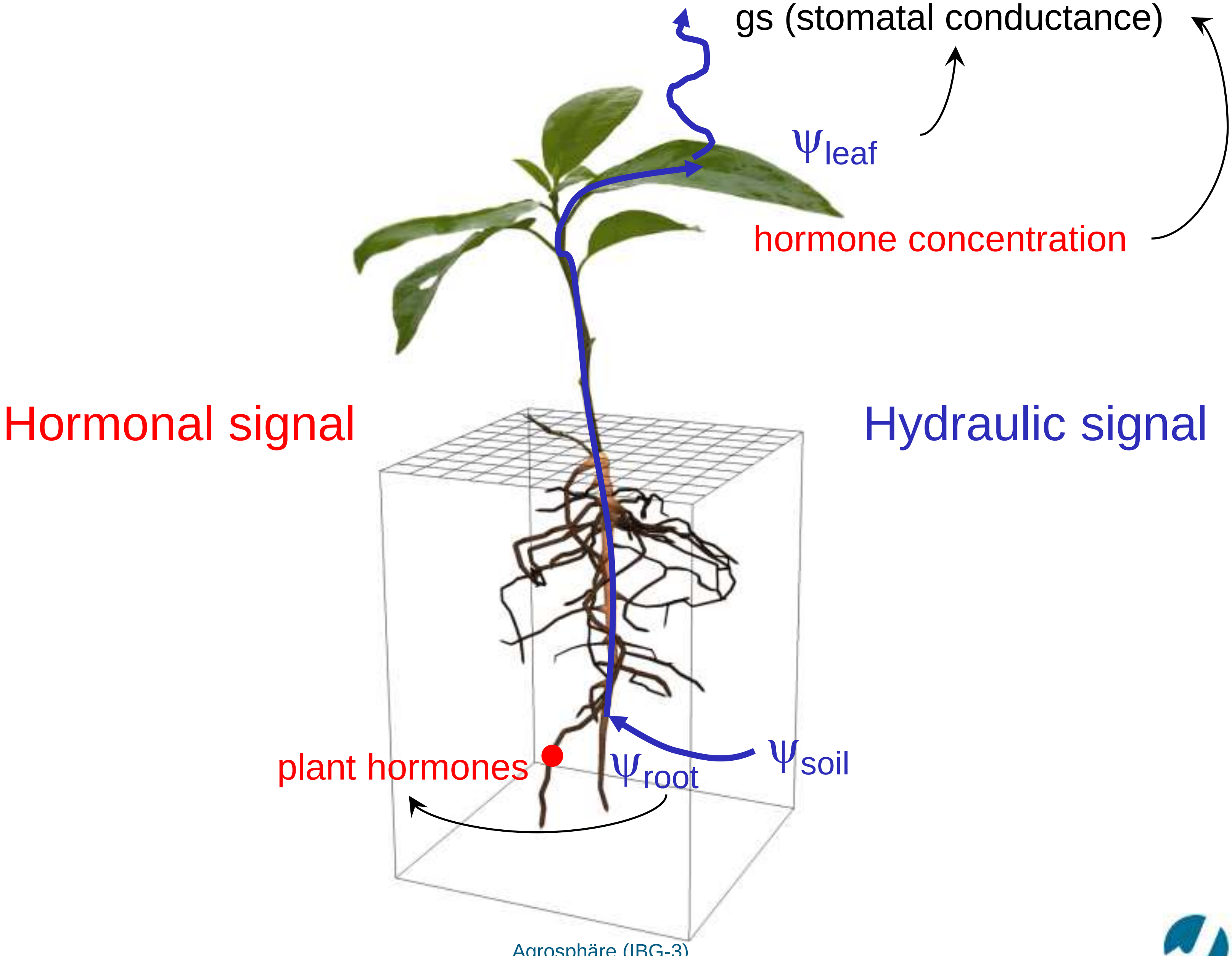
PLANT ROOT

<u>geometry</u>: tree-like structure with connected nodes



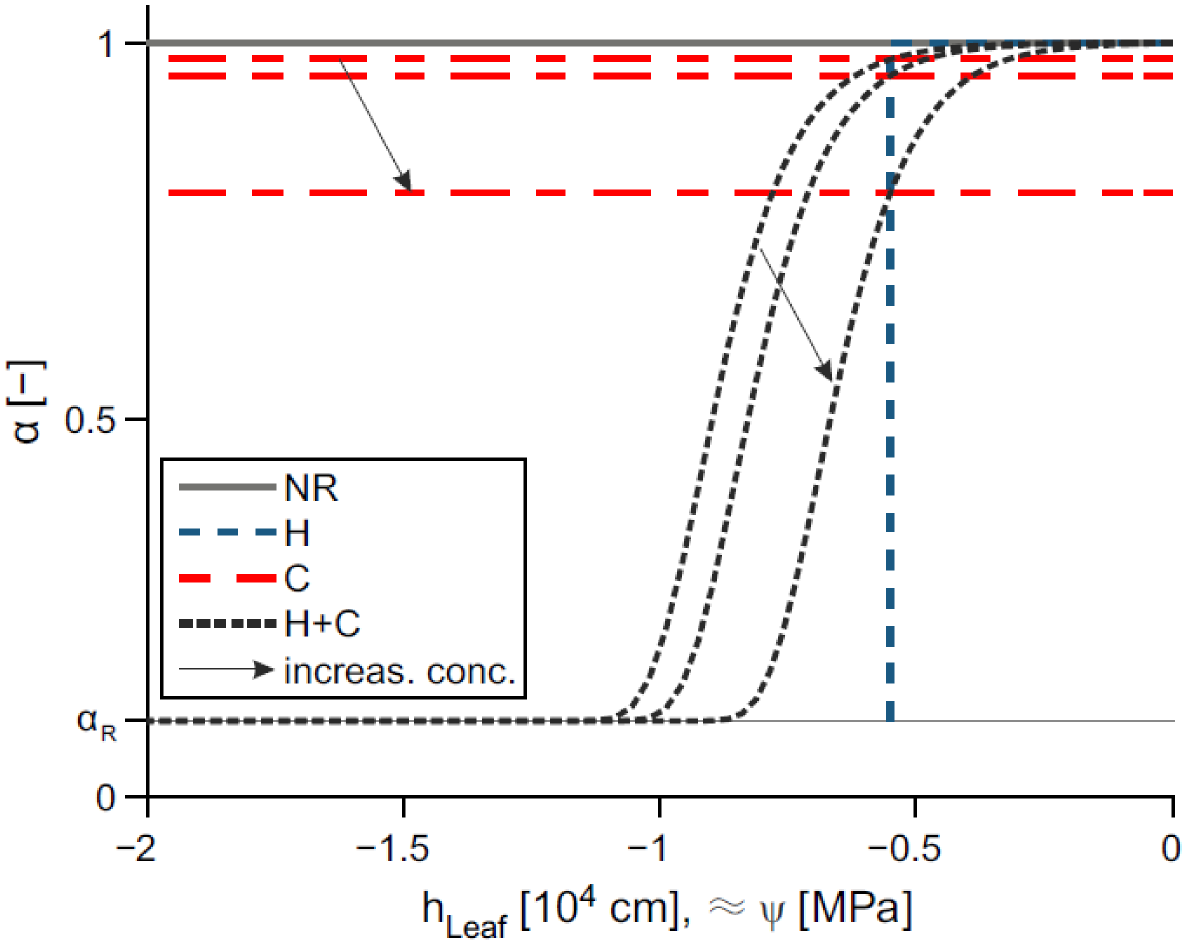
<u>numerics</u>: system of linear equations with boundary conditions given by the soil-root interface water potential ψ_s and the plant collar ψ/flux time series

How do Stomata ´Sense´ Soil Water Potentials?

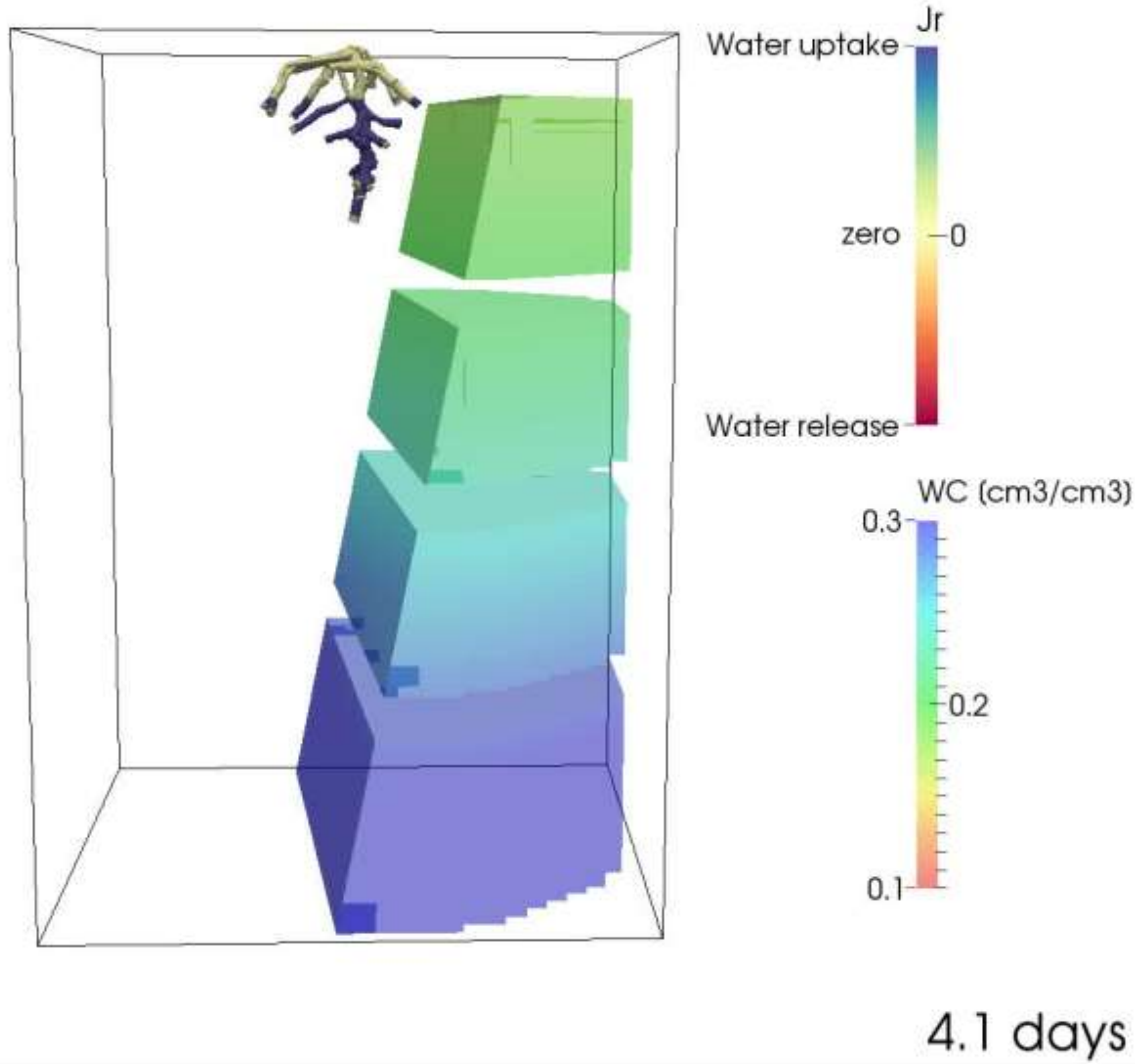


Upper Boundary Condition

Stress function α is the ratio of the transpiration rate of the plant compared to the transpiration rate if there would be sufficient water available.

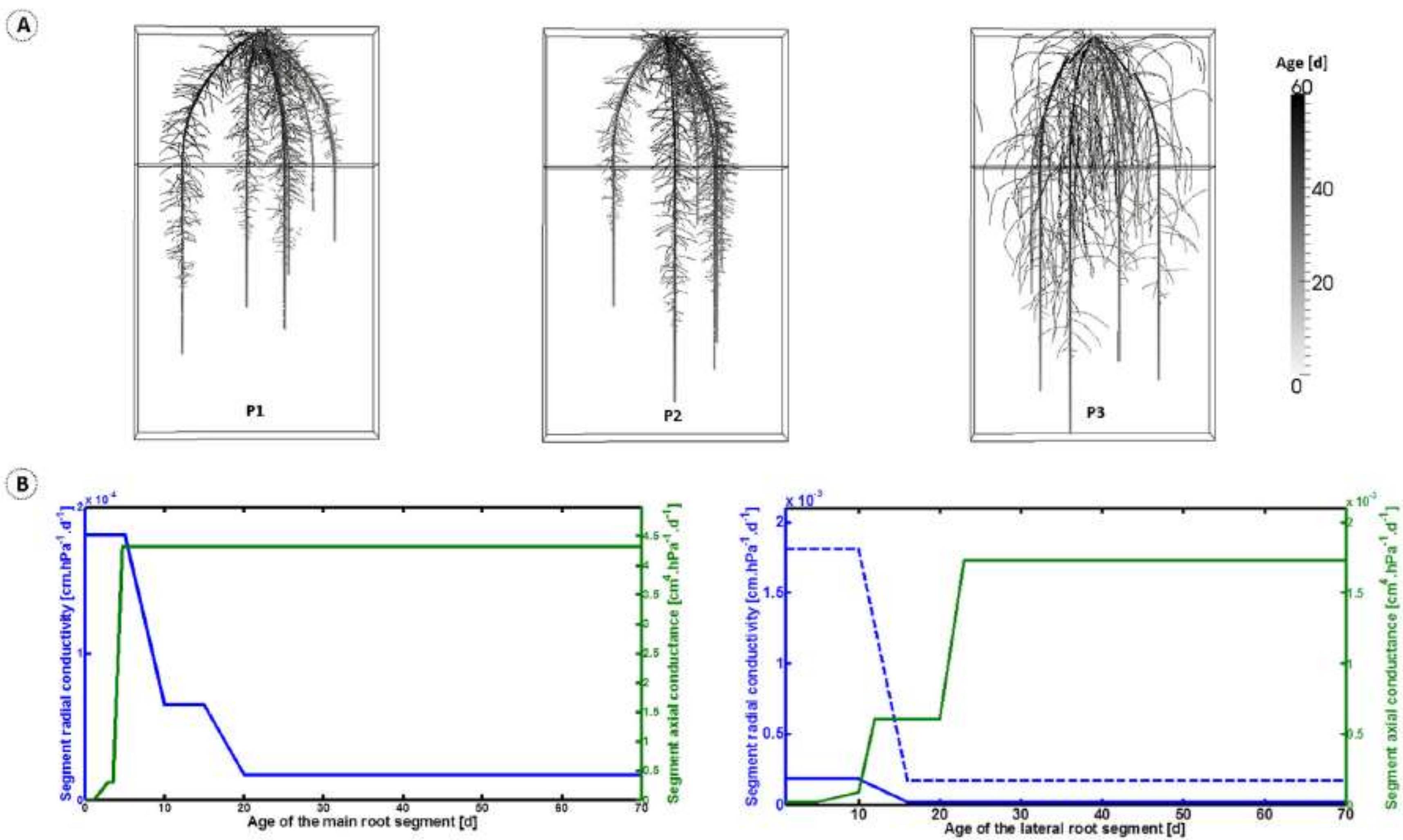


Modeling Root Water Uptake with R-SWMS



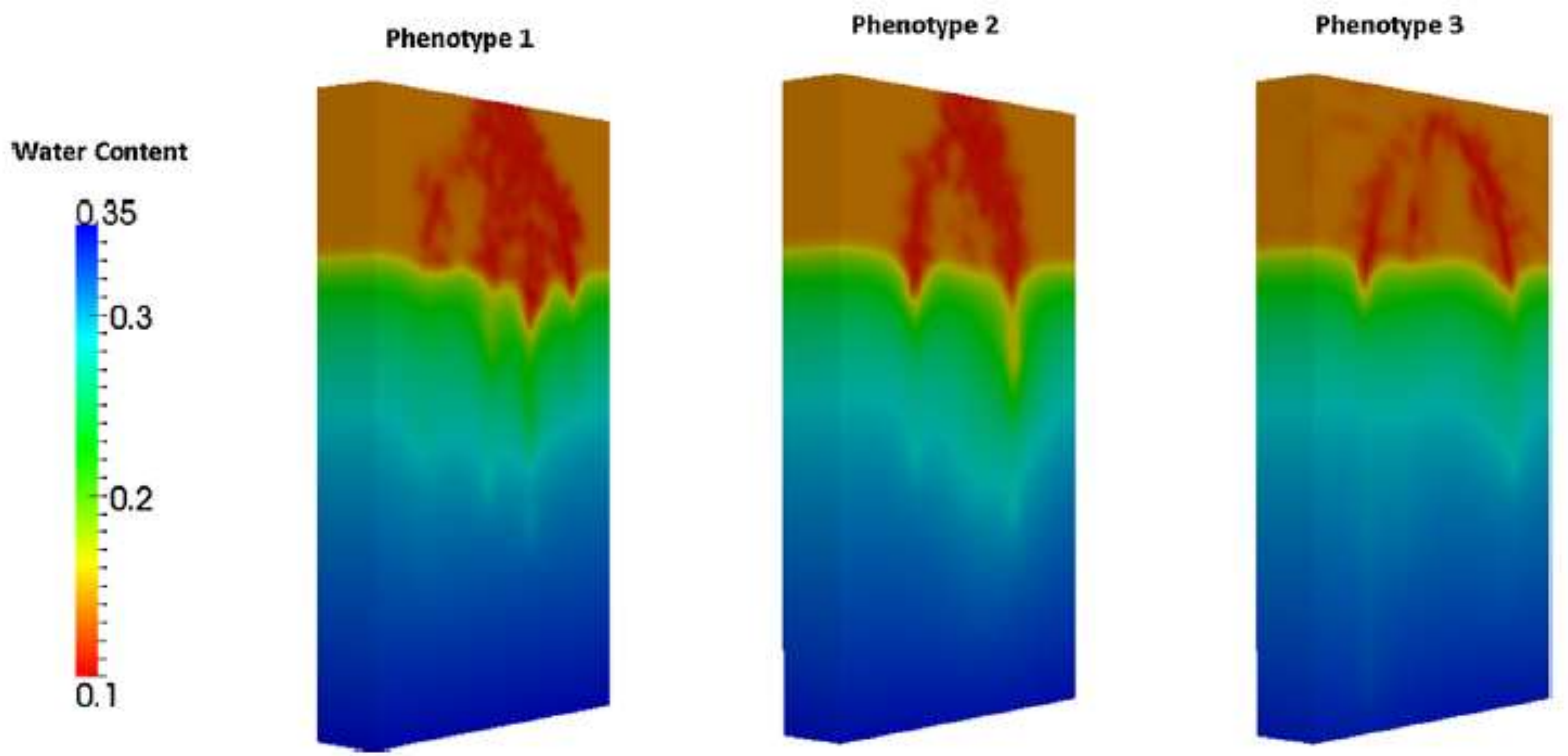
Köbernick et al., Frontiers in Plant Sciences (in press)

Effect of Root ´Phenotypes´ on Root Water Uptake



Leitner et al., 2014, Field Crops Research

Effect of Root ´Phenotypes´ on Root Water Uptake



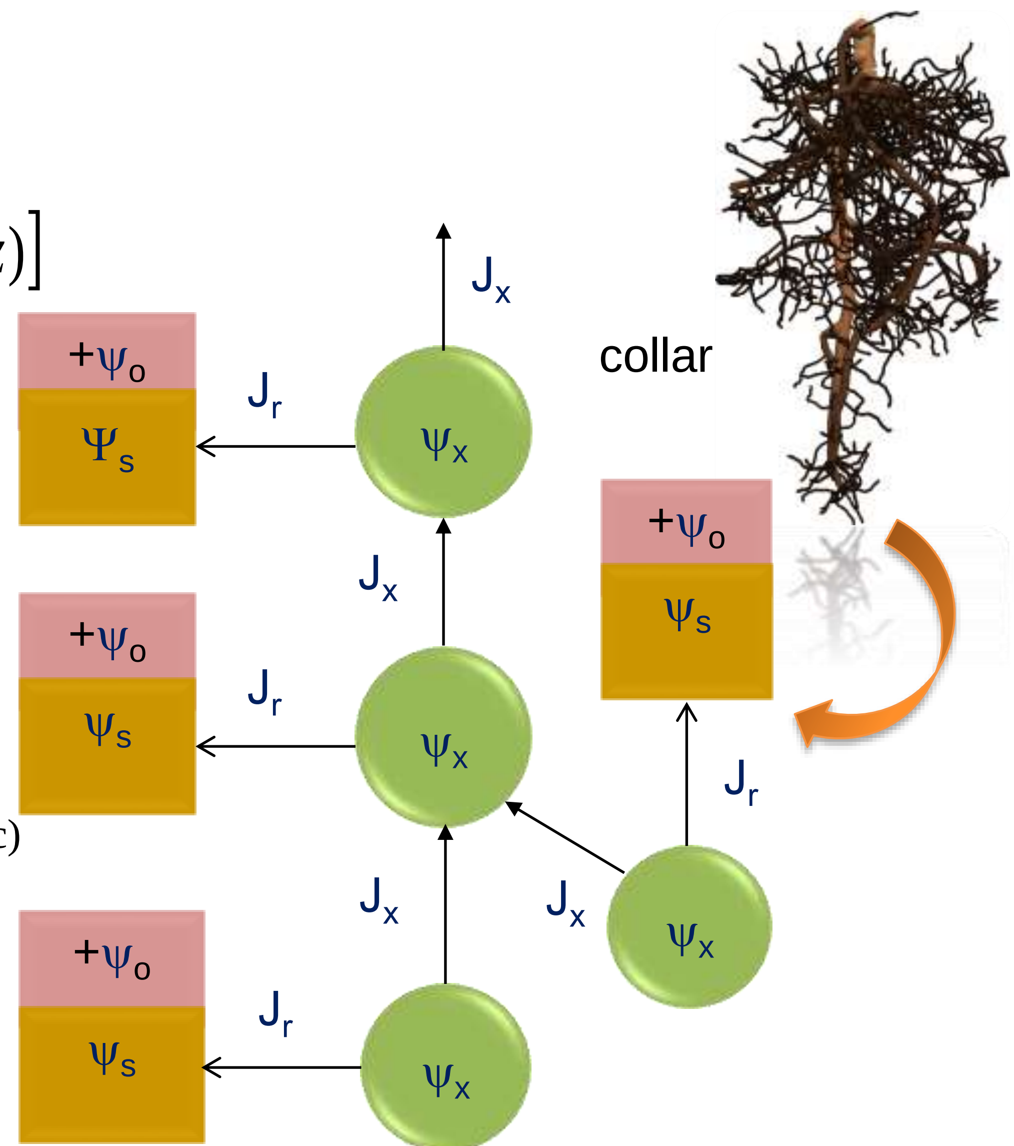
Effect of Salinity (Osmotic Head) on Root Water Uptake

Water flow across root:

$$J_r = K_r S_r \left[\psi_s(z) + \psi_o(z) - \psi_x(z) \right]$$

Water flow through xylem

$$J_x = -K_x A_x \frac{\Delta \psi_x(z)}{dl_{seg}}$$



ψ : water potential (surface | soil, xylem, osmotic)

K_r : intrinsic radial conductivity

K_x : intrinsic axial conductivity

S_r : root - soil interface area

A_x : xylem cross sectional area

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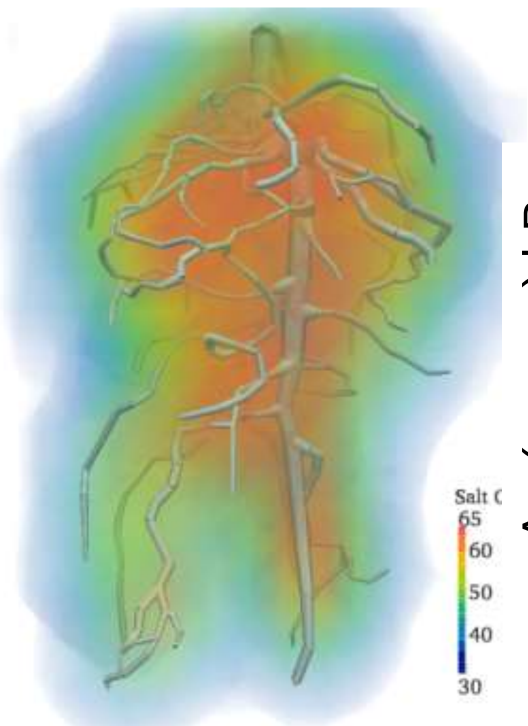
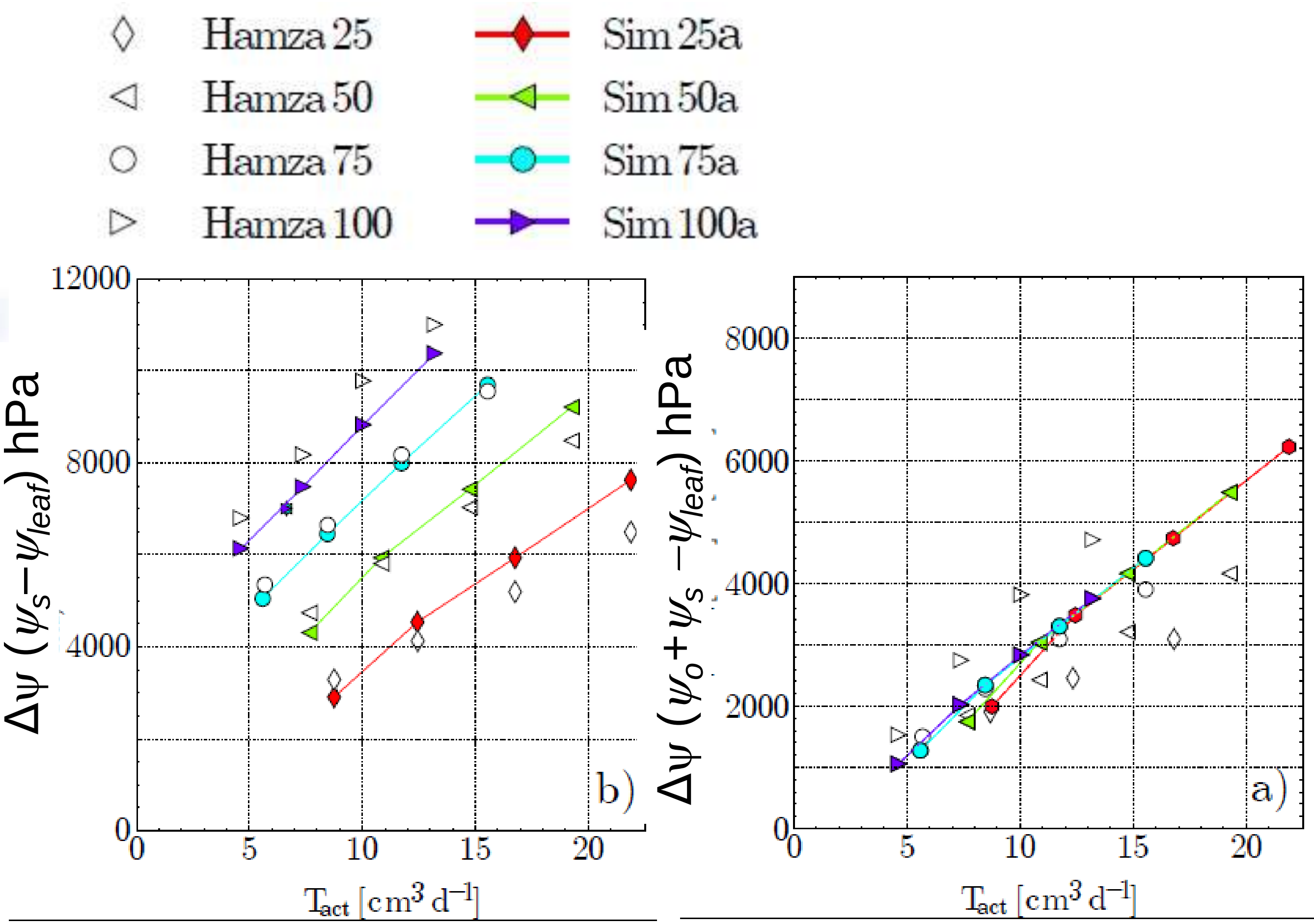
Effect of Salinity (Osmotic Head) on Root Water Uptake/ Transpiration





Schröder et al., Plant and Soil

Effect of Salinity (Osmotic Head) Combination with Matric Potential Stress?

$$\alpha(\psi,\psi_o)=\alpha(\psi+\psi_o)$$

or

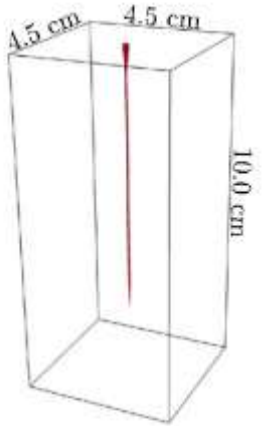
$$\alpha(\psi,\psi_o)=\alpha(\psi)\alpha_o(\psi_o)$$

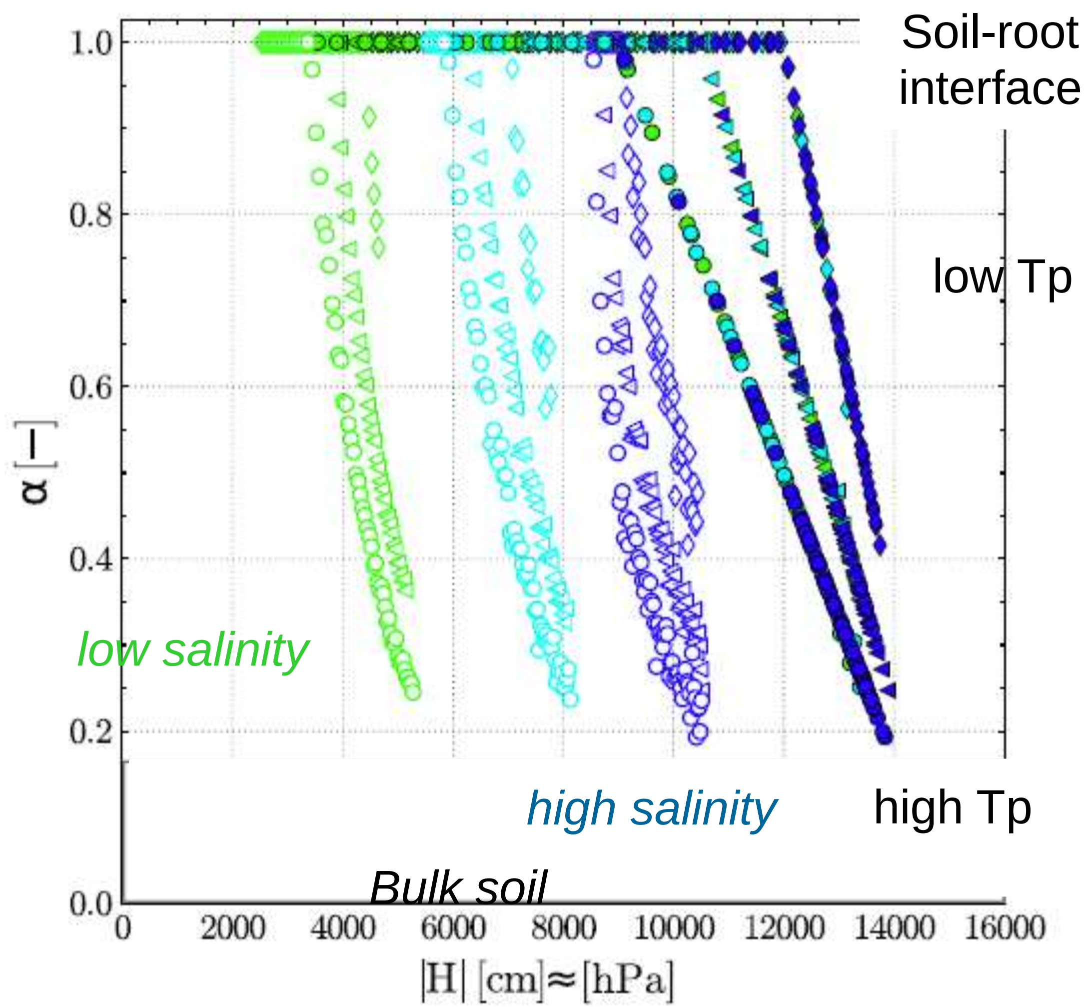
or

$$\alpha(\psi,\psi_o)=\min[\alpha(\psi),\alpha_o(\psi_o)]?$$

$\alpha = T_{act} / T_{pot}$

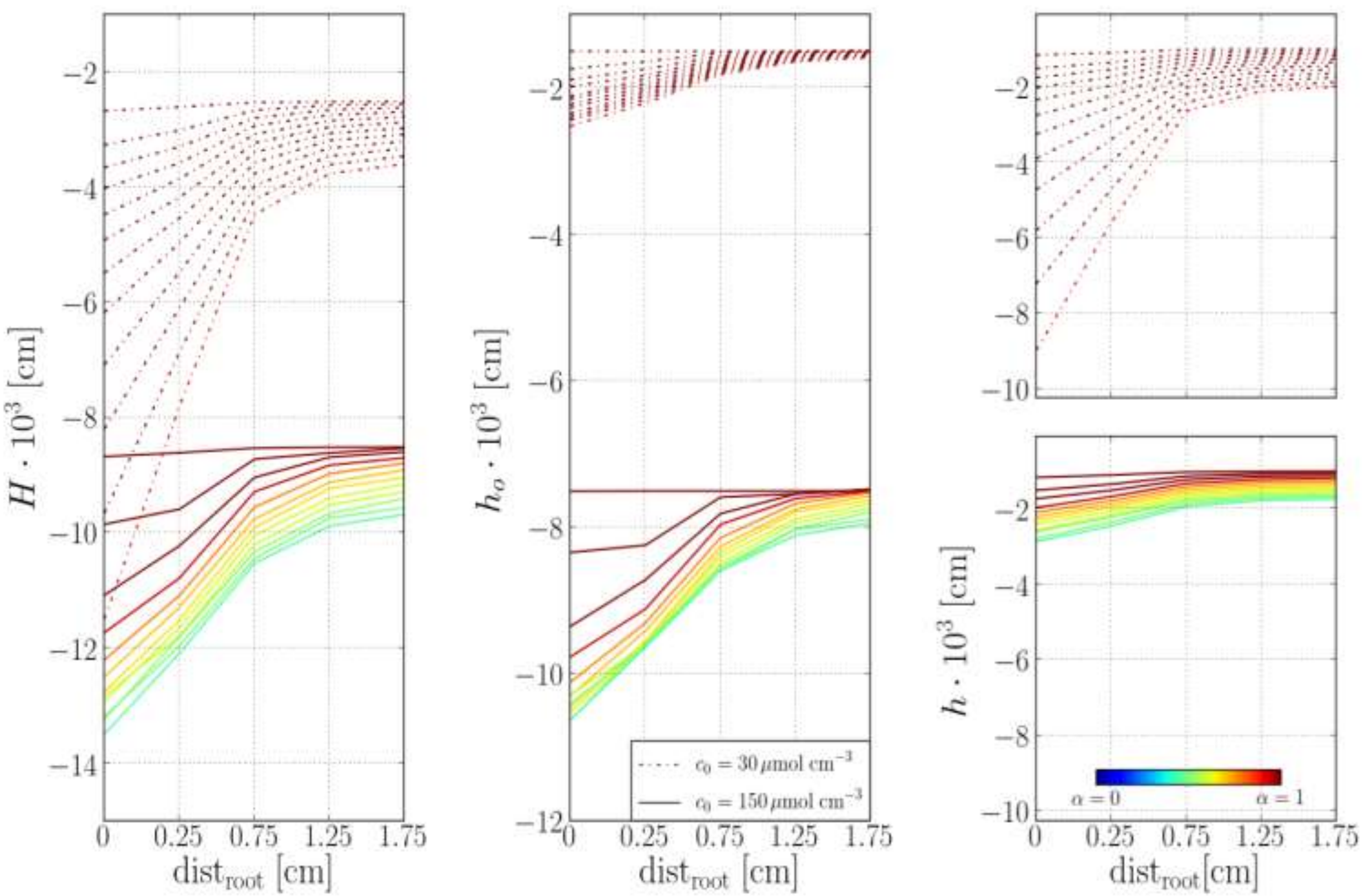
Simulations with R-SWMS: Single Root





Schröder et al. Plant and Soil (2013)

Simulations with R-SWMS: Single Root



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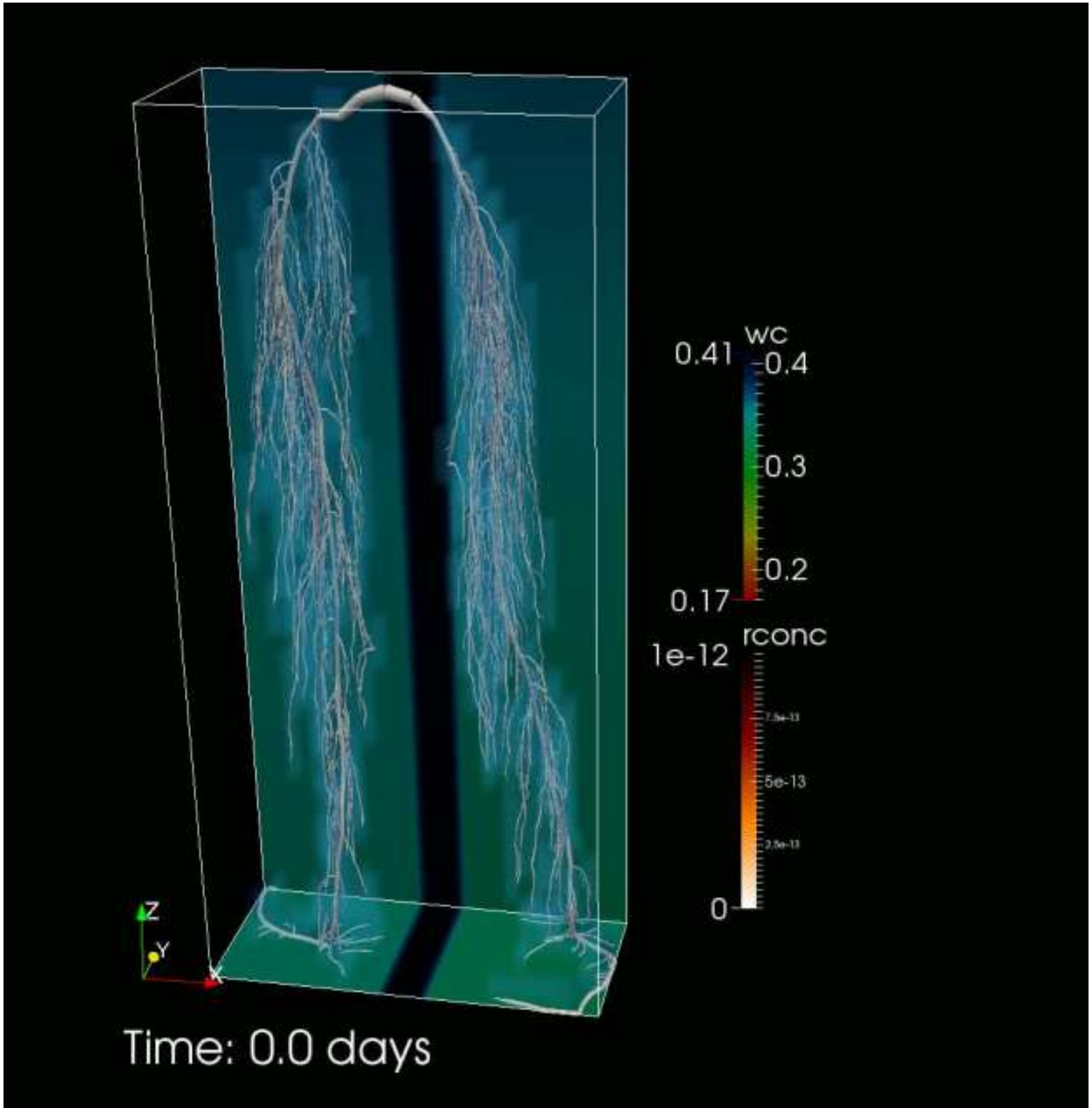
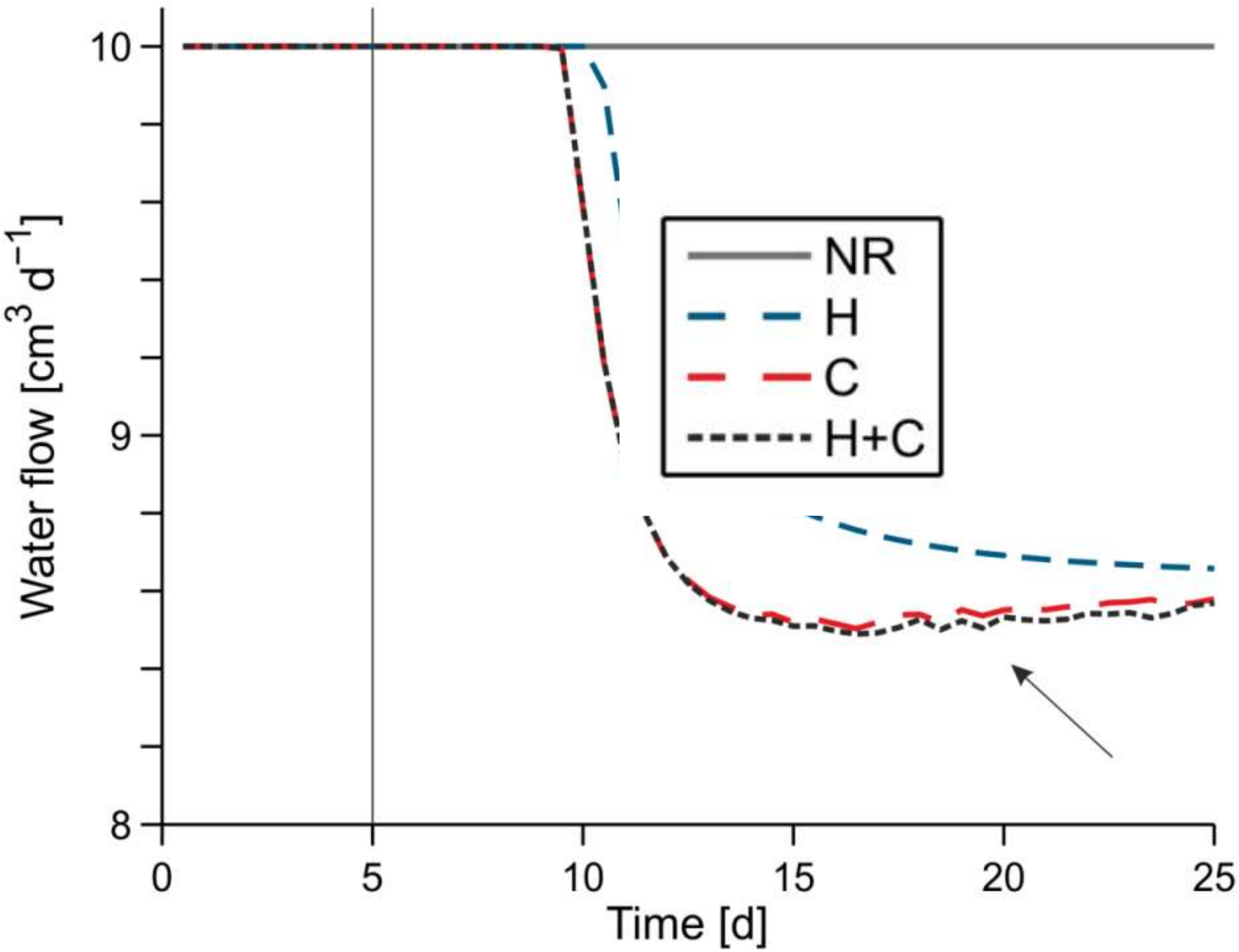
Hormonal Signaling

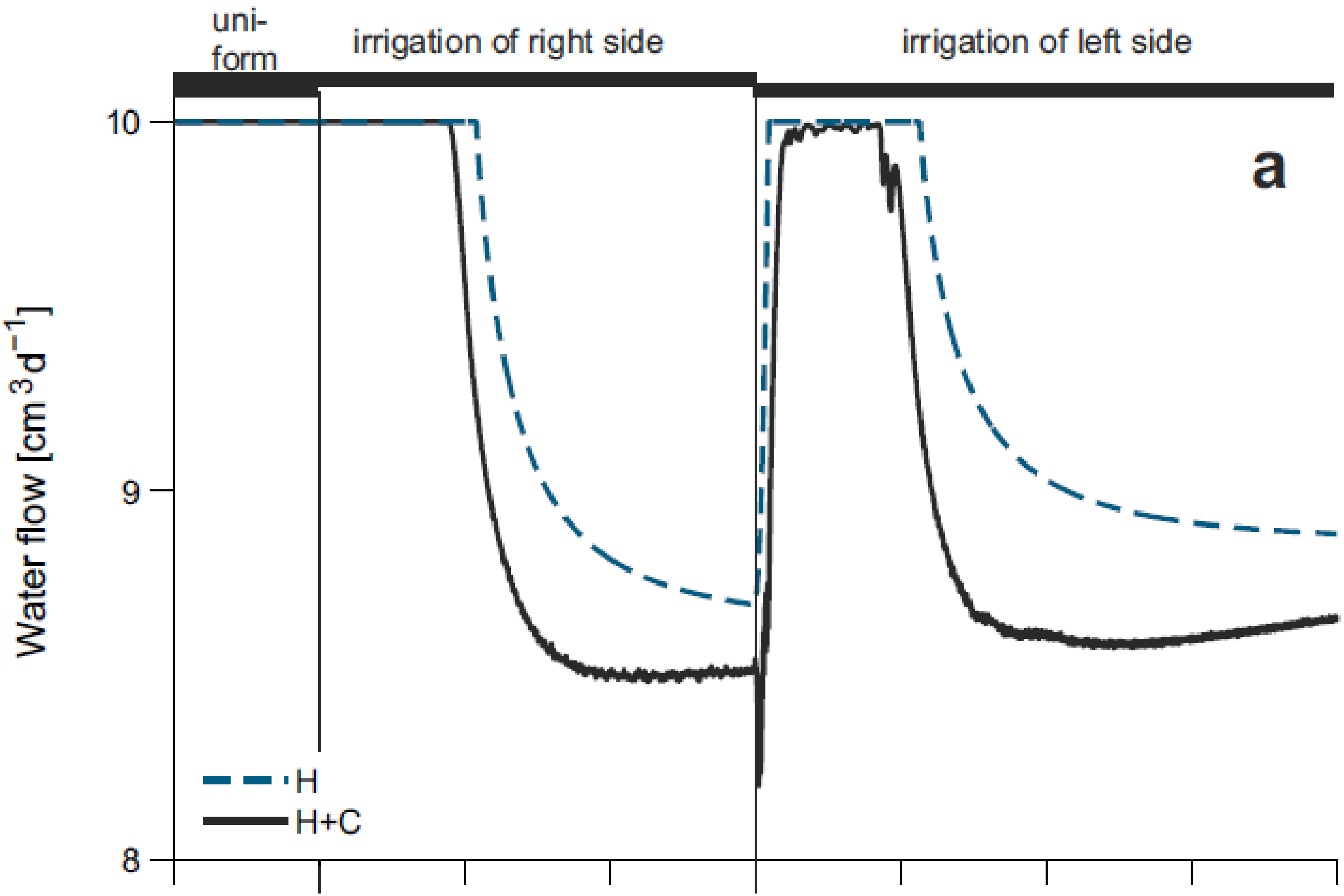


Hormonal Signaling and Partial Root Zone Drying

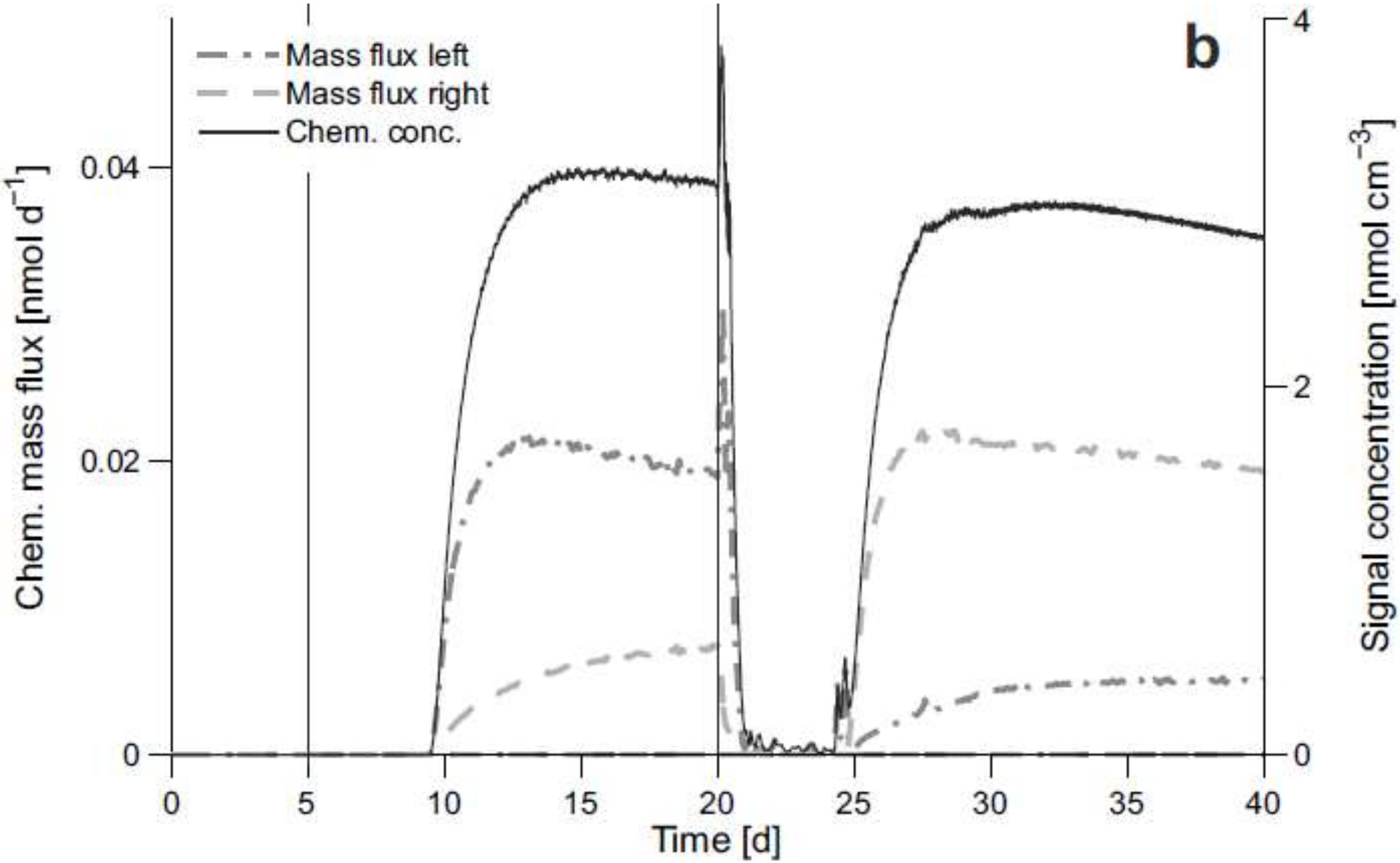


Huber et al., Plant and Soil (2014)

Hormonal Signaling and Alternated Root Zone Drying



Hormonal Signaling and Alternated Root Zone Drying



Using R-SWMS Simulations for Upscaling (Couvreur et al., HESS, 2012)

A simple approach to consider root hydraulic properties and root architecture in larger scale simulation models

$$T_a = K_{rs}\left(\overline{\psi}_{root} - \psi_{collar}\right)$$

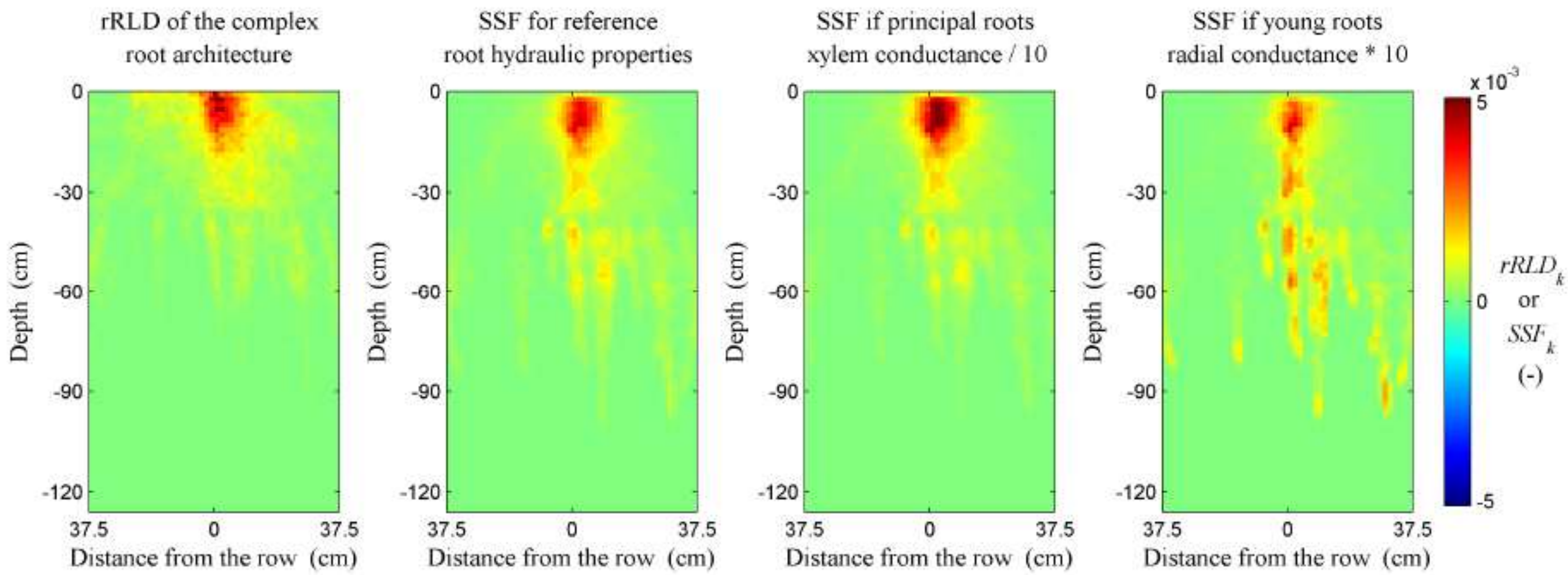
$$\overline{\psi}_{root} = \int_{\Omega_R} SSF(\mathbf{x})\psi_s(\mathbf{x})d\mathbf{x}$$

$$S(\mathbf{x}) = T_a SSF(\mathbf{x}) + SSF(\mathbf{x})K_{comp}\left(\psi_s(\mathbf{x}) - \overline{\psi}_{root}\right)$$

K_{rs}: root system‘s conductance
SSF: standardized sink fraction (uptake for uniform water potential)
ψ_{collar}: water potential at the collar
$\overline{\psi}_{root}$: water potential felt by the root system

- For a given ψ_{collar}, T_a does not depend on T_p
- S(x) is non-local: depends also on ψ at other locations
- S(x) can be negative → roots exude water → hydraulic lift.

Relation between SSF and Hydraulic Properties of the Root System



SSF is different from RLD
SSF depends on hydraulic root parameters

Couvreur et al., 2012, HESS

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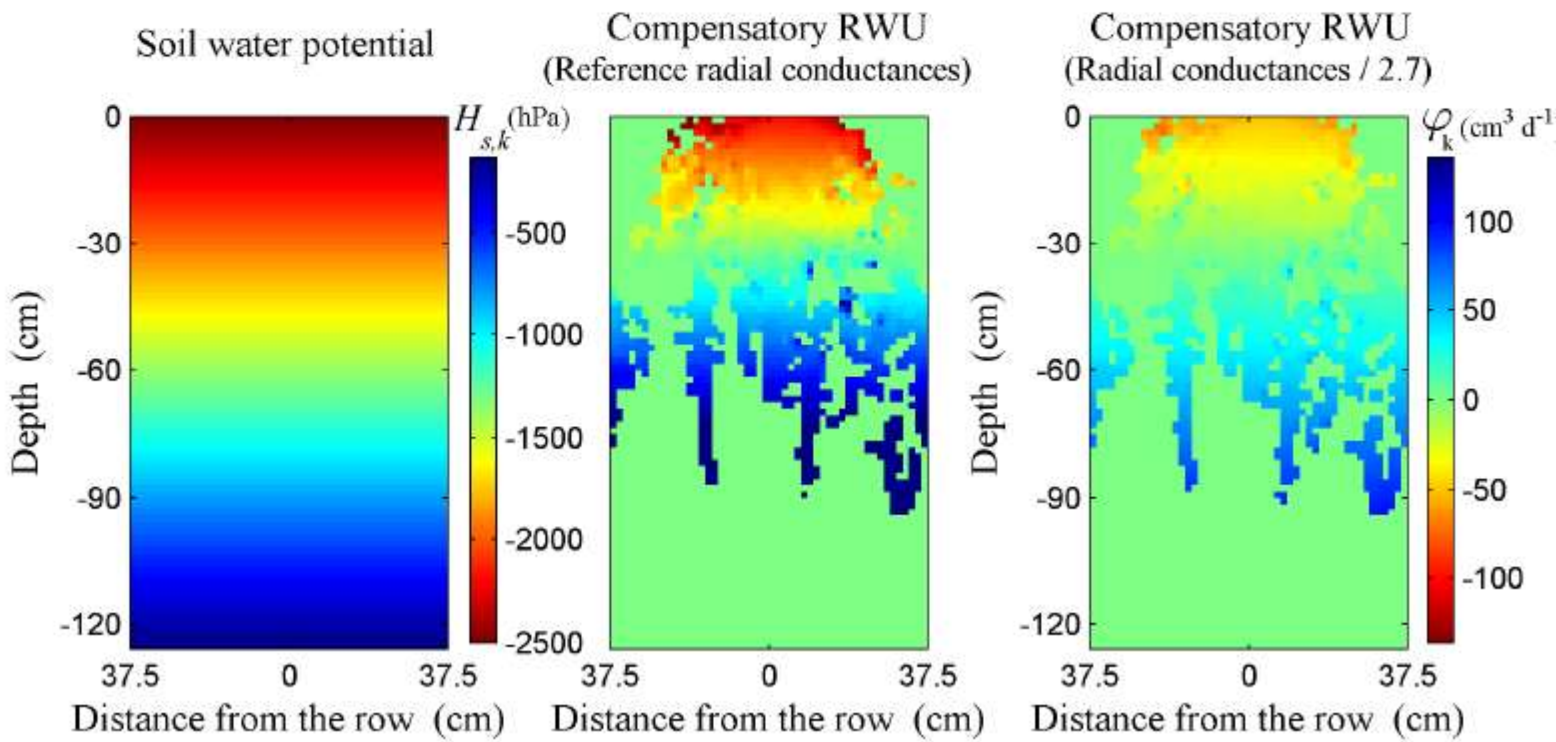
Simulation of RWU Compensations

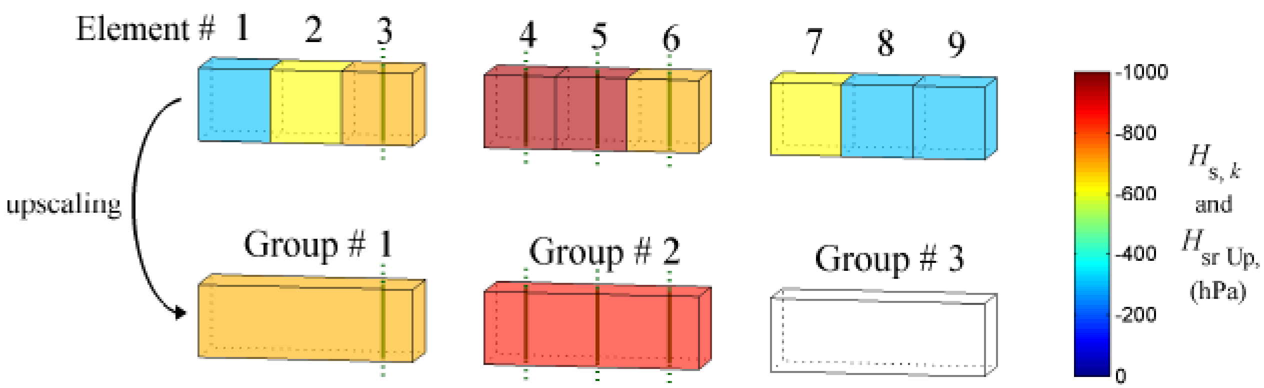


- RWU compensation does not require a complex parameterisation.
- Occurence of RWU compensation does not depend on mean root zone water potential → not related to ‚local' water stress.
- Also exudation is predicted (hydraulic lift)

Couvreur et al., 2012

Upscaling from 3-D to 1-D

$$SSF_{up}(\mathbf{x}) = \frac{1}{\Omega_{up}} \int_{\Omega_{up}} SSF(\mathbf{x})\, d\mathbf{x} \qquad \psi_{root,up}(\mathbf{x}) = \frac{\int_{\Omega_{up}} SSF(\mathbf{x}) \psi_s(\mathbf{x})\, d\mathbf{x}}{\int_{\Omega_{up}} SSF(\mathbf{x})\, d\mathbf{x}}$$



$$S_{up}(\mathbf{x}) = \frac{T_{act}}{\Omega_{up}} \int_{\Omega_{up}} SSF(\mathbf{x})\, d\mathbf{x} + \frac{K_{comp}}{\Omega_{up}} \int_{\Omega_{up}} SSF(\mathbf{x})[\psi_s(\mathbf{x}) - \bar{\psi}_{root}]\, d\mathbf{x}$$

$$S_{up}(\mathbf{x}) = T_{act} SSF_{up}(\mathbf{x}) + K_{comp} SSF_{up}(\mathbf{x})\left[\psi_{root,up}(\mathbf{x}) - \bar{\psi}_{root}\right]$$

Problem: how to compute $\psi_{root,up}(\mathbf{x})$ and $\bar{\psi}_{root}$ when information about small scale variation of $\psi_s(\mathbf{x})$ is not available?

Upscaling Assumptions

$$\frac{1}{\Omega_{up}}\int_{\Omega_{up}} SSF(\mathbf{x})\psi_s(\mathbf{x})\,d\mathbf{x} \approx \frac{1}{\Omega_{up}}\int_{\Omega_{up}} SSF(\mathbf{x})\,d\mathbf{x}\;\frac{1}{\Omega_{up}}\int_{\Omega_{up}} \psi_s(\mathbf{x})\,d\mathbf{x}$$

$$\psi_{root,up}(\mathbf{x}) \approx \frac{1}{\Omega_{up}}\int_{\Omega_{up}} \psi_s(\mathbf{x})\,d\mathbf{x} = \psi_{s,up}(\mathbf{x})$$

$$\bar{\psi}_{root} \approx \frac{1}{\Omega_R}\int_{\Omega_R} SSF_{up}(\mathbf{x})\psi_{s,up}(\mathbf{x})\,d\mathbf{x}$$

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi_{s,up})\frac{\partial\psi_{s,up}}{\partial z}\right] - S_{up}(z,t)$$

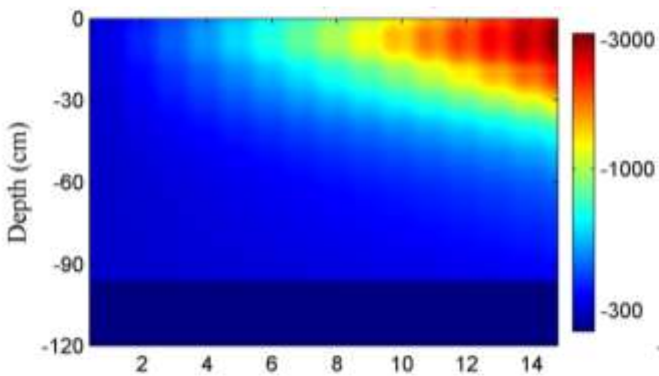
$$S_{up}(\mathrm{z}) = T_{act}SSF_{up}(\mathrm{z}) + K_{comp}SSF_{up}(\mathrm{z})\left[\psi_{s,up}(\mathrm{z}) - \bar{\psi}_{root}\right]$$

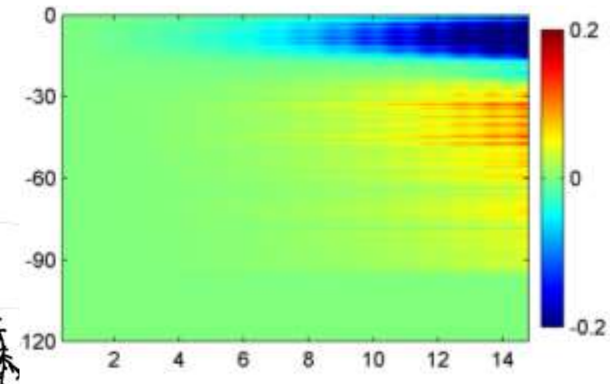
Upscaling from 3-D to 1-D: Wheat

$$\psi_{root,up} = \frac{\int_{\Omega} SSF(\mathbf{x})\psi_{root}(\mathbf{x})\, d\mathbf{x}}{\int_{\Omega} SSF(\mathbf{x})\, d\mathbf{x}}$$

$$K_{comp} SSF_{up}(\mathbf{x})\left[\psi_{root,up}(\mathbf{x}) - \bar{\psi}_{root}\right]$$

3-D

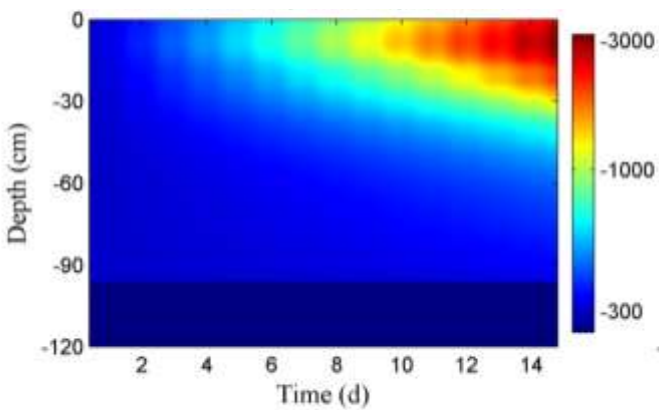


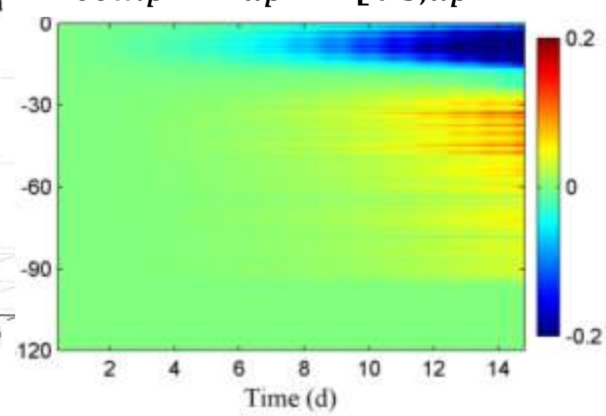


$$\psi_{root,up} \approx \psi_{s,up} = \frac{1}{\Omega}\int_{\Omega} \psi_s(\mathbf{x})\, d\mathbf{x}$$

$$K_{comp} SSF_{up}(\mathbf{x})\left[\psi_{s,up}(\mathbf{x}) - \bar{\psi}_{root}\right]$$

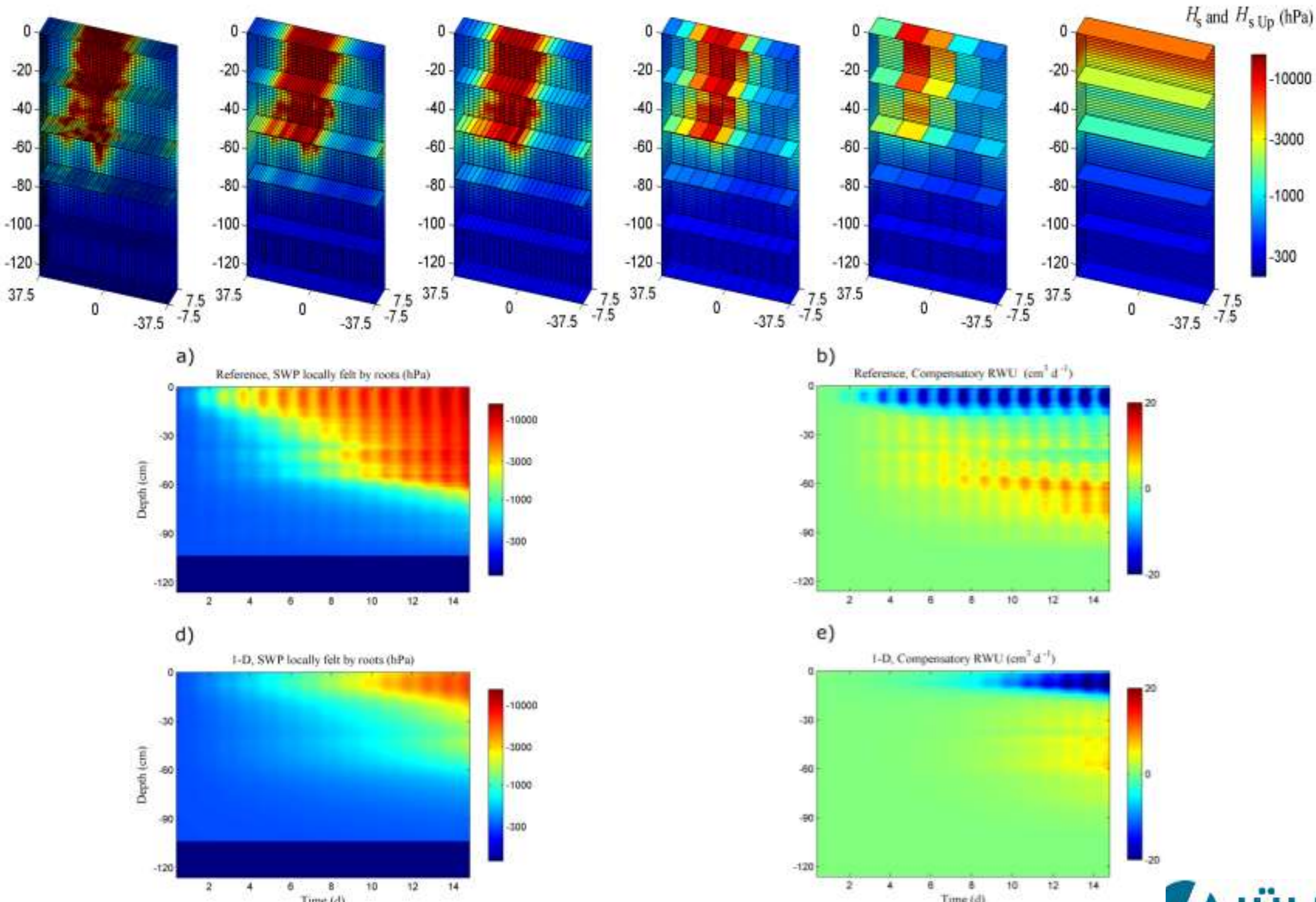
1-D



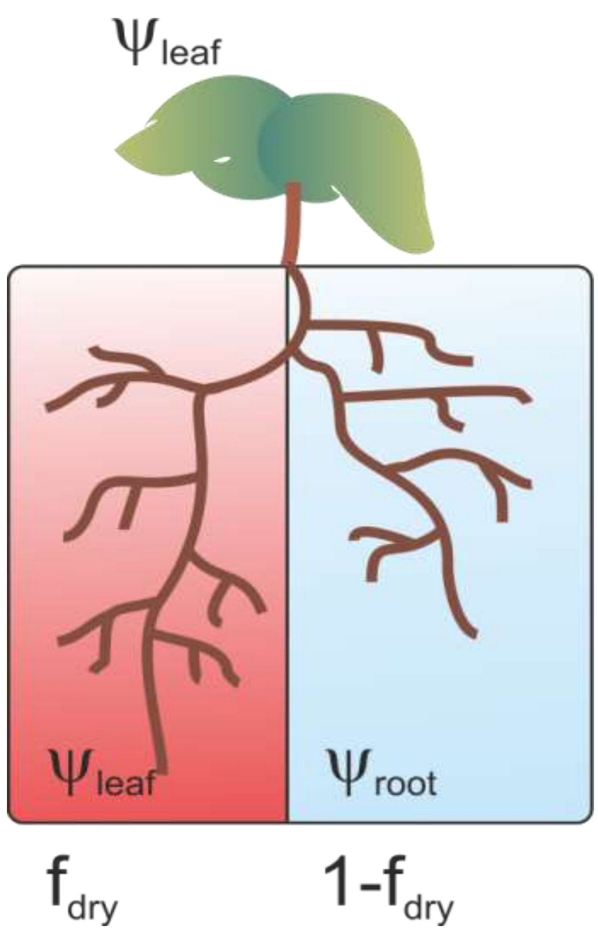


Couvreur et al., 2014, HESS

Upscaling from 3-D to 1-D: Maize with Row-Interrow Variability?



Hormonal vs. Hydraulic Signaling and Plant-Scale Behavior



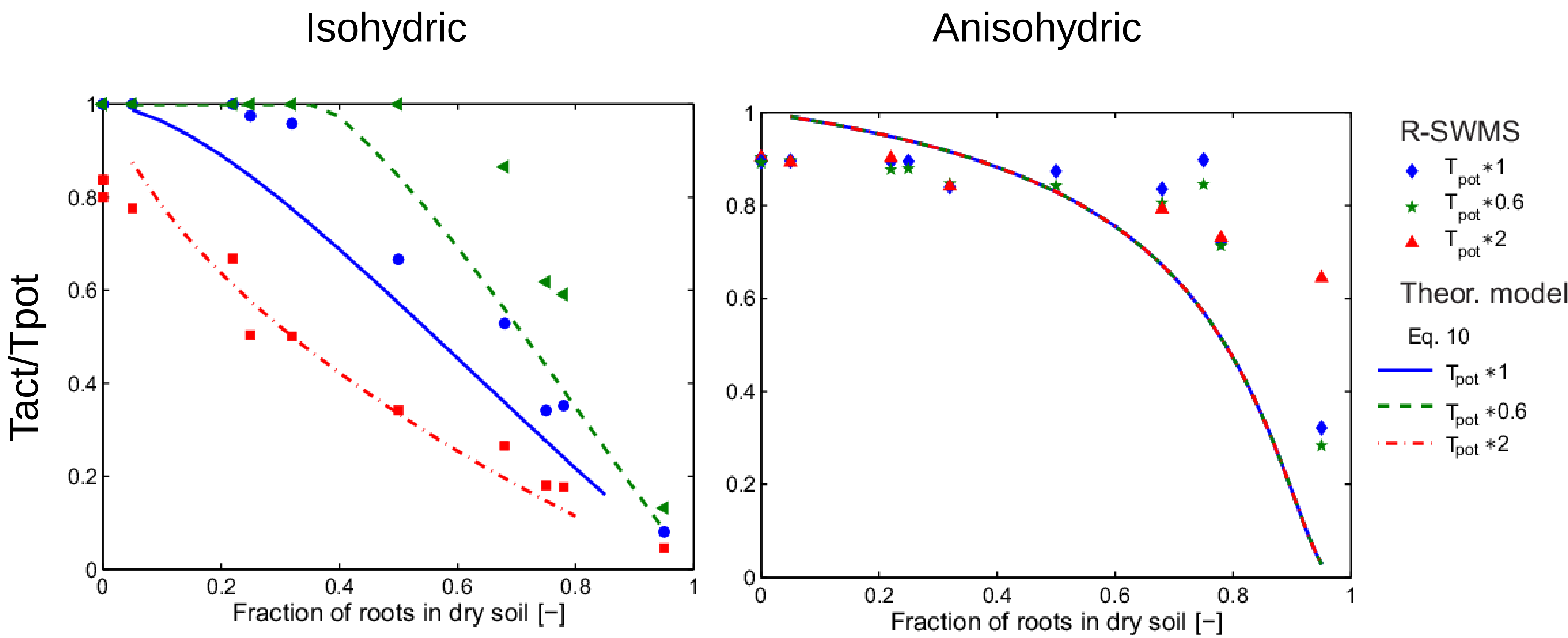
Two plant types:

- *Isohydric plants*: stomatal conductance depends on leaf water potential and on hormone concentrations in the leaves
- *Anisohydric plants*: stomatal conductance depends only on hormone concentrations.

Different scenarios:

- Root fraction in wet/dry soil
- Transpiration rate

Hormonal vs. Hydraulic Signaling and Plant-Scale Behavior



Huber et al., 2015, Plant and Soil

Some Final ´Statements´

Models should be as simple as possible

… but not simpler. Albert Einstein

Lack of data must not be a motivation to simplify models

… it should rather be a motivation to improve our experimental methods.

THANK YOU!

Gaochao Cai
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R-SWMS
Modeling Root-Soil Water Movement and Solute transport

JÜLICH FORSCHUNGSZENTRUM