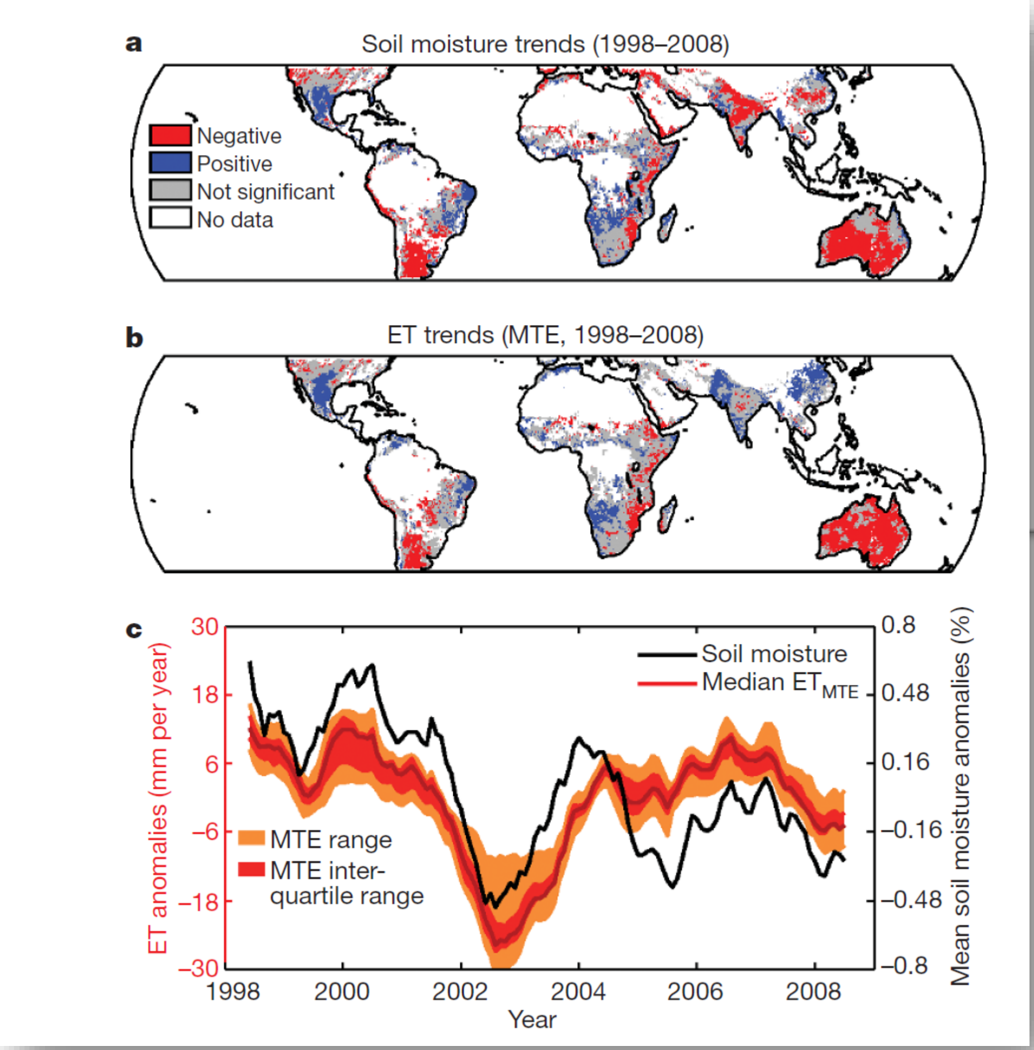
Modelling soil and plant hydraulic resistances from root to field scale

Mathieu Javaux

Earth and Life Institute, Université catholique de Louvain, Belgium

Agrosphere IBG-3, Forschungszentrum Juelich GmbH, Germany

Soil water and transpiration



LETTER

doi:10.1038/nature09396

Recent decline in the global land evapotranspiration trend due to limited moisture supply

Martin Jung[1], Markus Reichstein[1], Philippe Ciais[2], Sonia I. Seneviratne[3], Justin Sheffield[4], Michael L. Goulden[5], Gordon Bonan[6], Alessandro Cescatti[7], Jiquan Chen[8], Richard de Jeu[9], A. Johannes Dolman[9], Werner Eugster[10], Dieter Gerten[11], Damiano Gianelle[12], Nadine Gobron[13], Jens Heinke[11], John Kimball[14], Beverly E. Law[15], Leonardo Montagnani[16], Qiaozhen Mu[17], Brigitte Mueller[3], Keith Oleson[6], Dario Papale[18], Andrew D. Richardson[19], Olivier Roupsard[20], Steve Running[17], Enrico Tomelleri[1], Nicolas Viovy[2], Ulrich Weber[1], Christopher Williams[21], Eric Wood[4], Sönke Zaehle[1] & Ke Zhang[14]

Impact of water deficit on transpiration

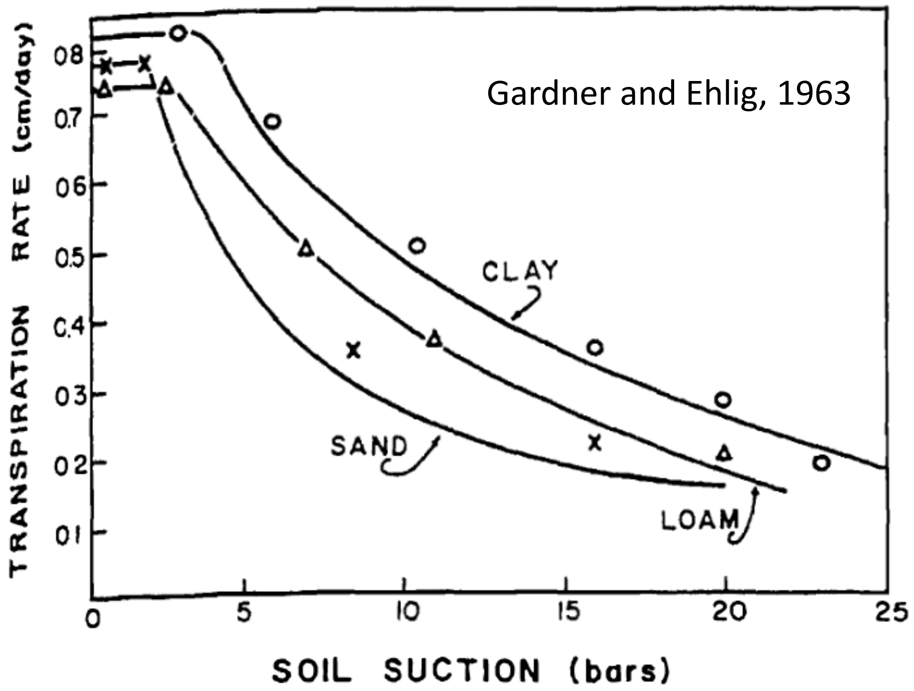


Fig. 4. Average daily transpiration rate for birdsfoot trefoil in shallow containers as a function of soil suction. The symbols represent experimental values obtained from Figure 2. The smooth curves were calculated theoretically. The soils are the same as for Figure 2.

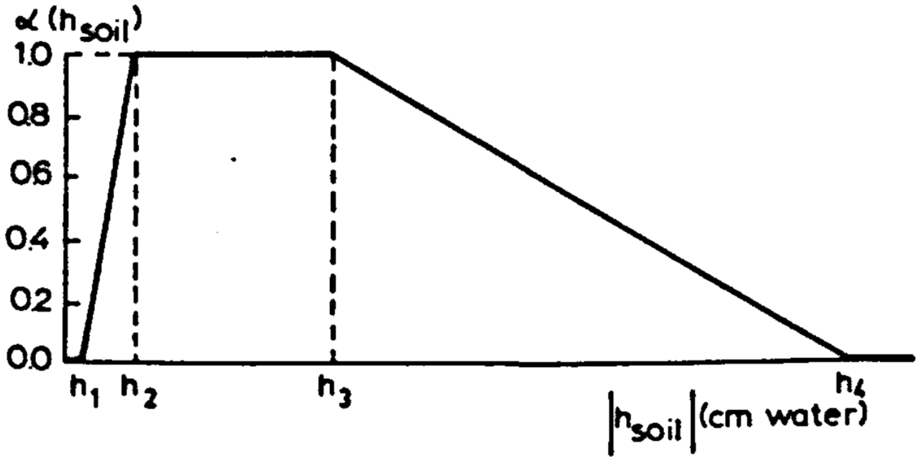
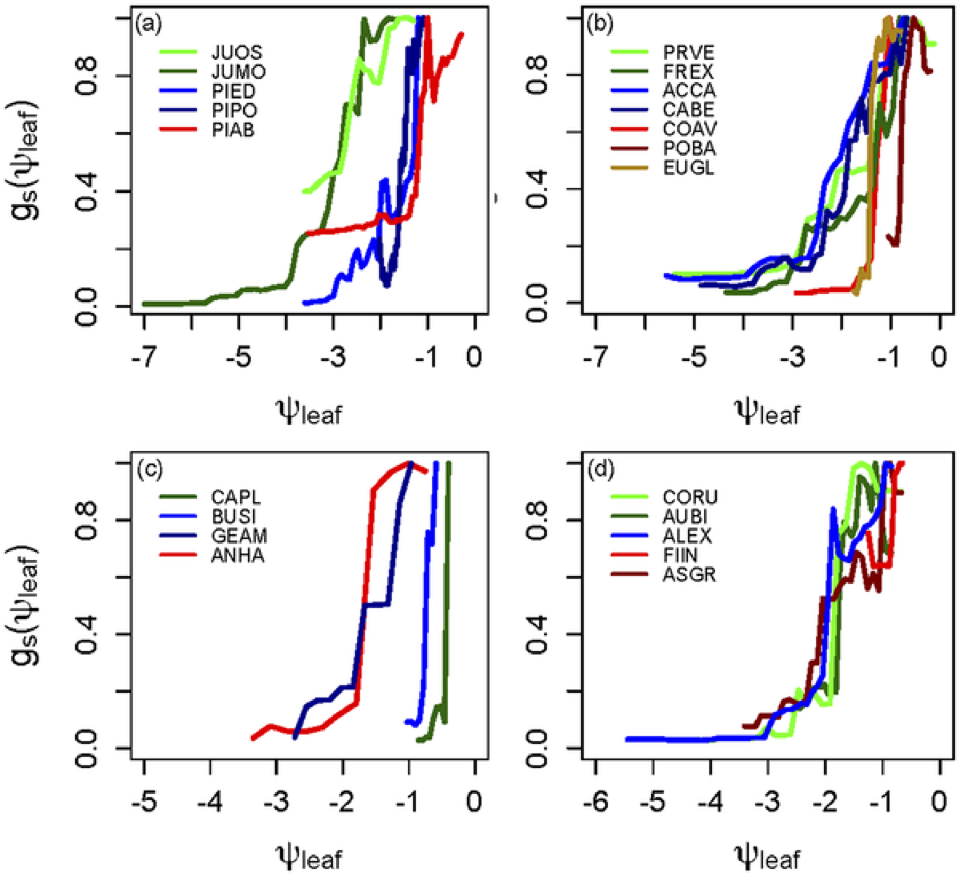


Figure 59. General shape of the dimensionless sink term variable, $\alpha(h)$, as a function of the absolute soil water pressure head, h (Feddes et al., 1978).

Stomtal resistance



Partial dependency of stomatal conductance (gs) on measured leaf water potential (ψleaf, in MPa) in (a) temperate gymnosperm species, (b) temperate angiosperm species, (c) tropical deciduous species, and (d) tropical evergreen species.

Anderegg et al., 2017

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Objectives

- Understand the key factors controlling uptake by roots and transpiration dynamics.
- Develop simplified but biophysically sound representations of plant water dynamics in terrestrial, crop or soil hydrological models
- Develop tools to help tackle soil-plant water management problems.

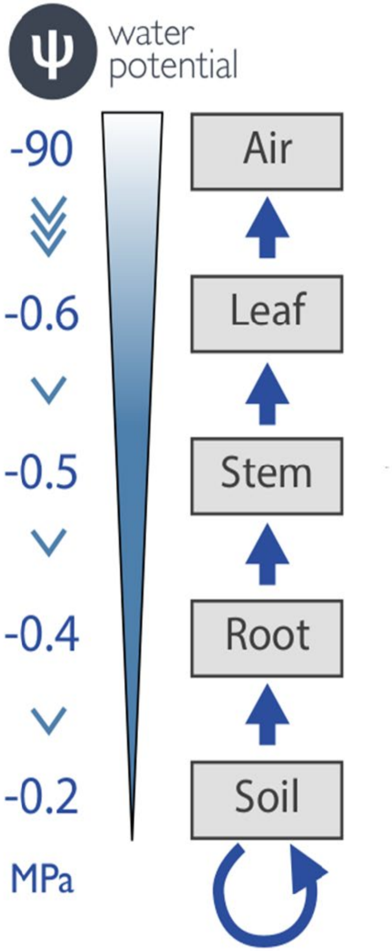
Outline

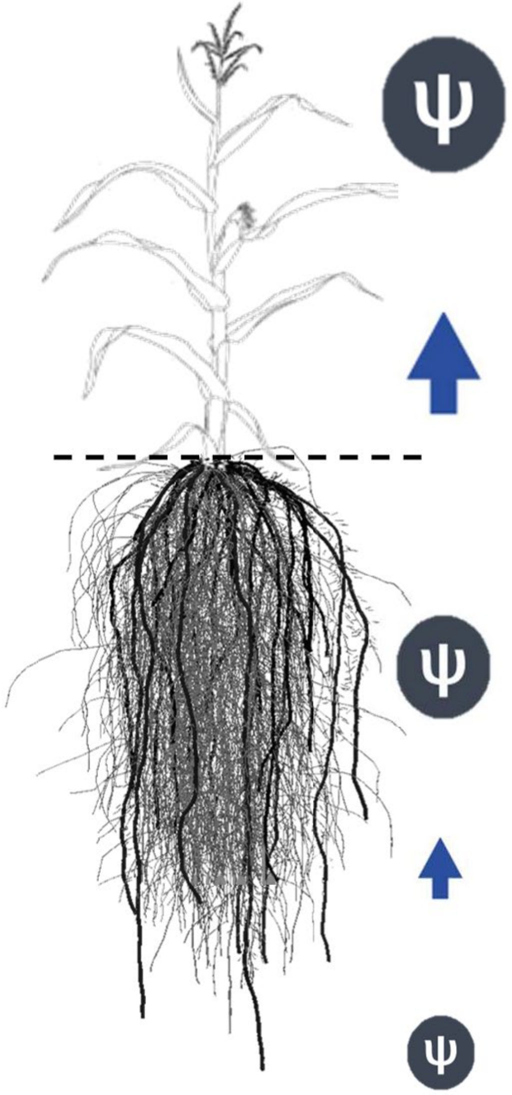
- 3D root system hydraulic architecture
- From explicit to implicit RSHA:
  - Root system scale parameters (Couvreur)
  - From local traits to root system parameters
- Adding rhizosphere resistance – root activity
- Conclusions

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Principles of water flow in the soil-plant system

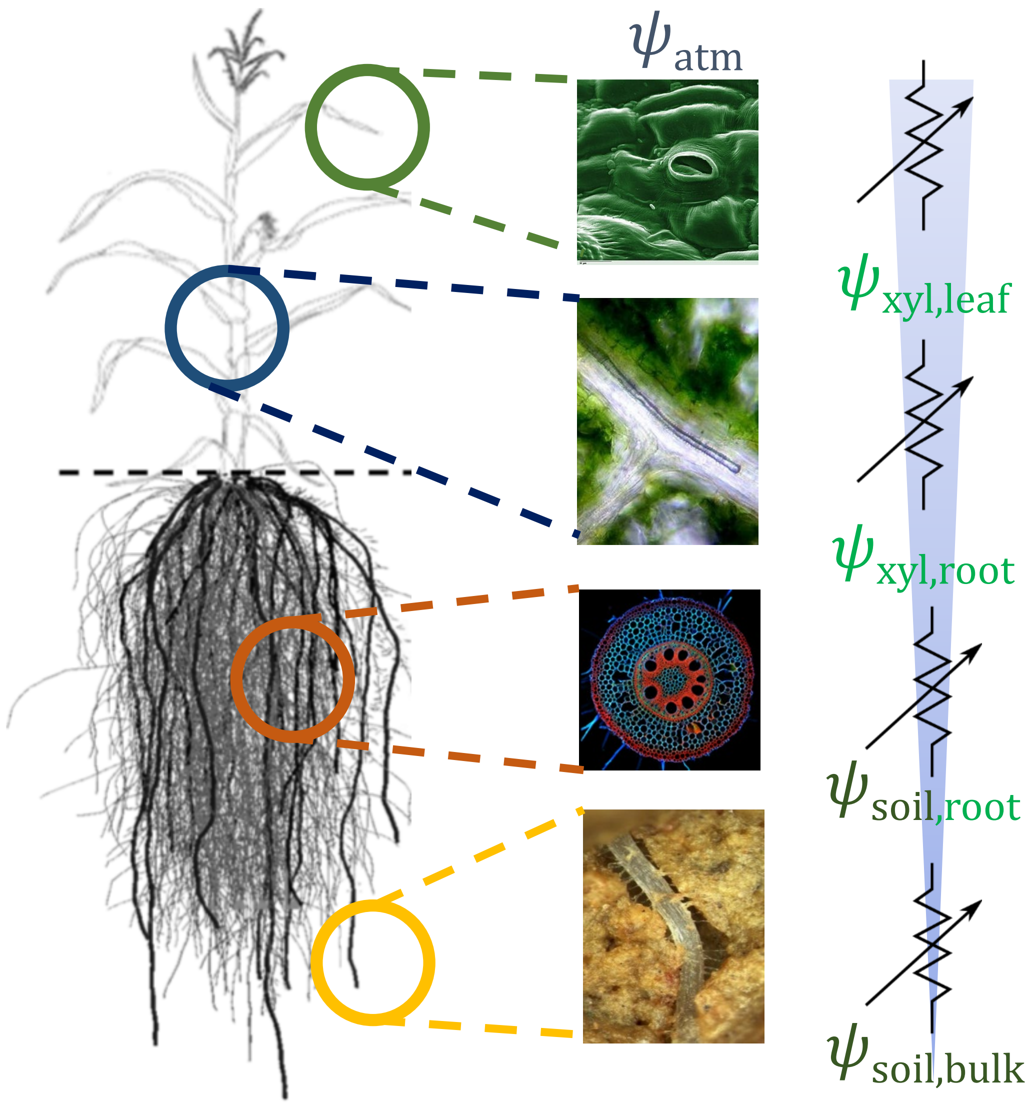
Between bulk soil and the atmosphere, the water flows towards lower water potential





UCLouvain JÜLICH FORSCHUNGSZENTRUM

Water flow resistances in the SPAC



Stomatal conductance

Xylem conductance

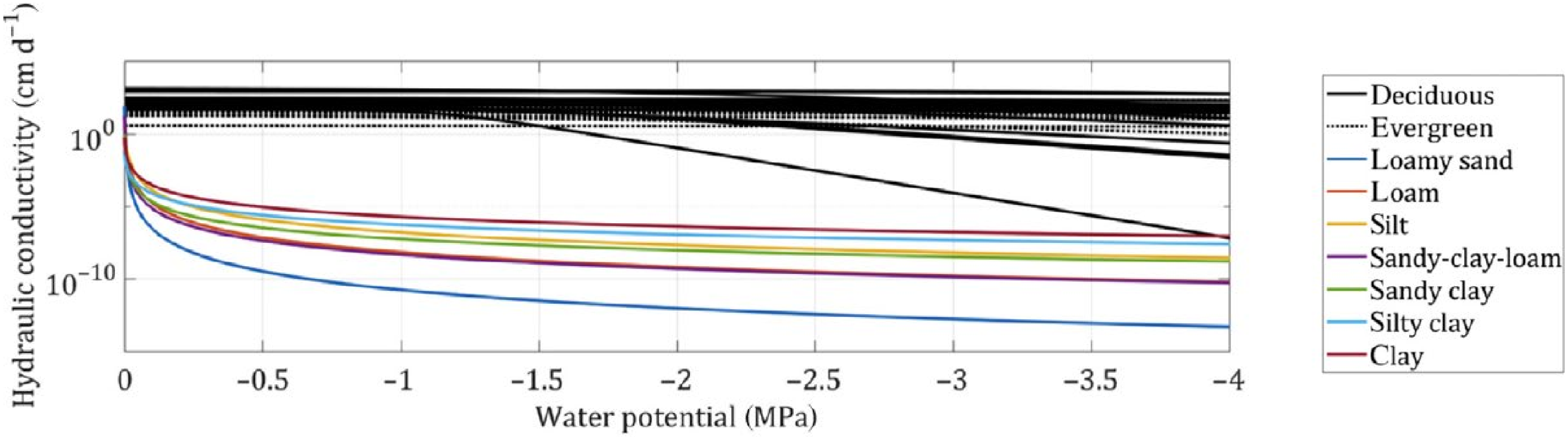
Root conductance

Rhizosphere conductance

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Main resistances

xylem vs. soil hydraulic conductivity

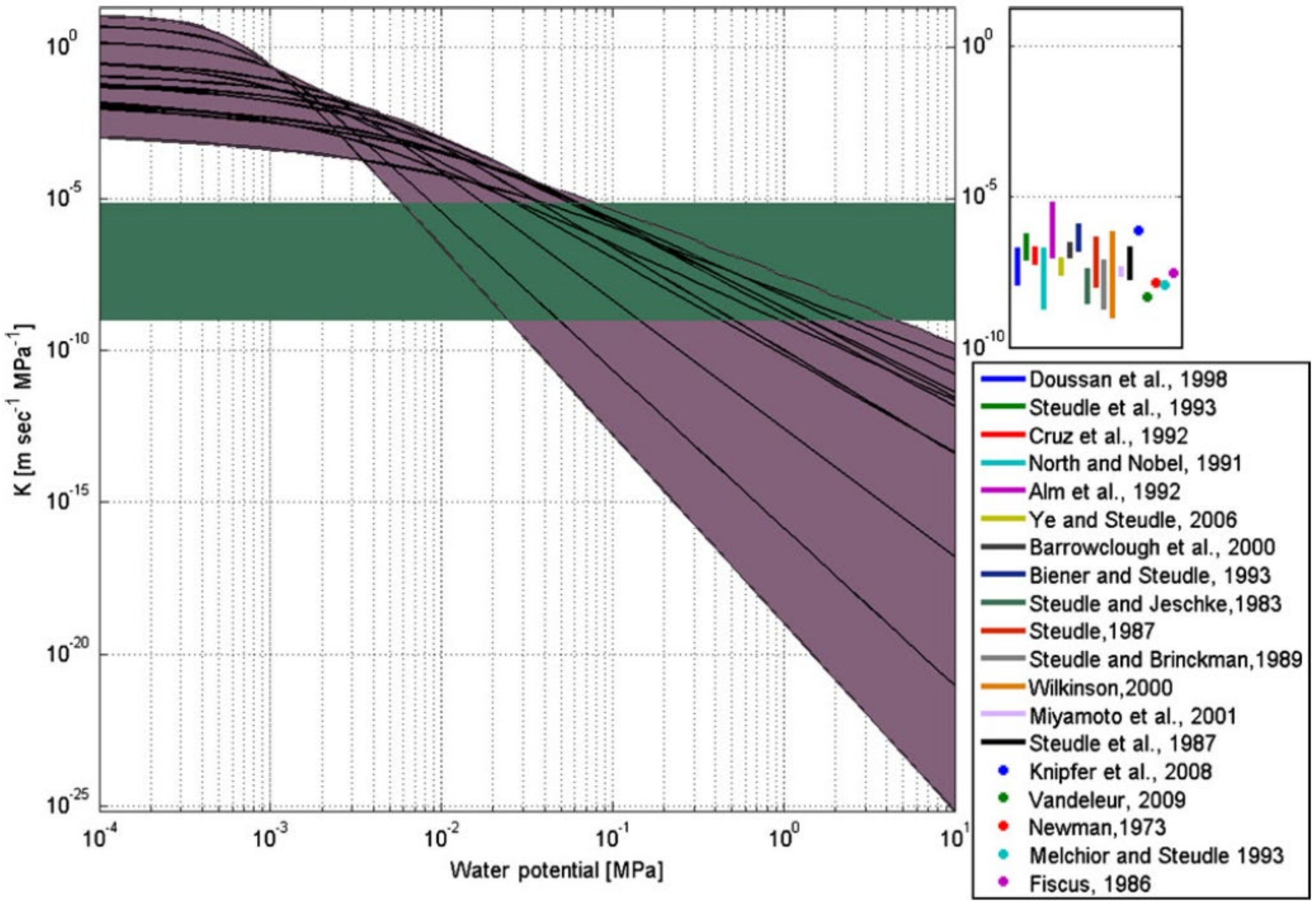


Carminati and Javaux, TiPS, 2020

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Main resistances

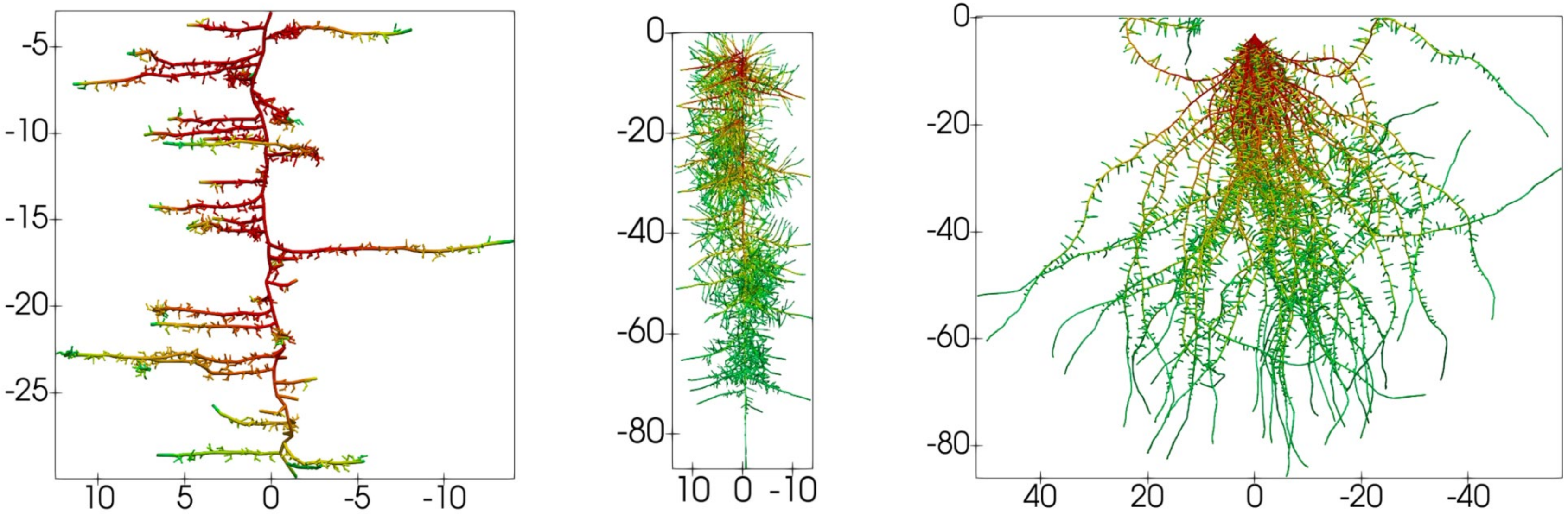
Radial root vs. soil hydraulic conductivity



Draye et al. JExpBot, 2010

Root hydraulic architecture: root system

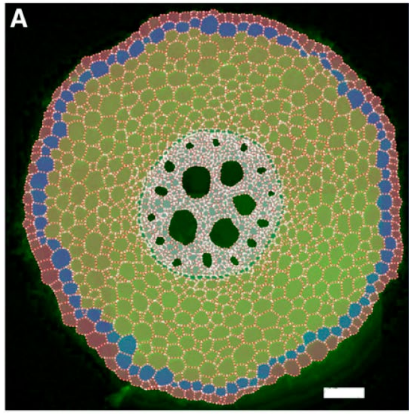
- Root topology (fibrous, taproots,…)
- Root types/orders
- Root depth or RLD
- Plasticity

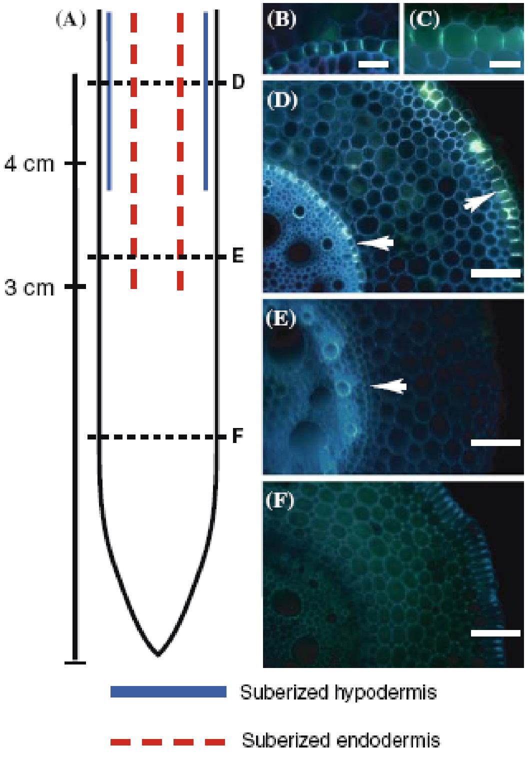


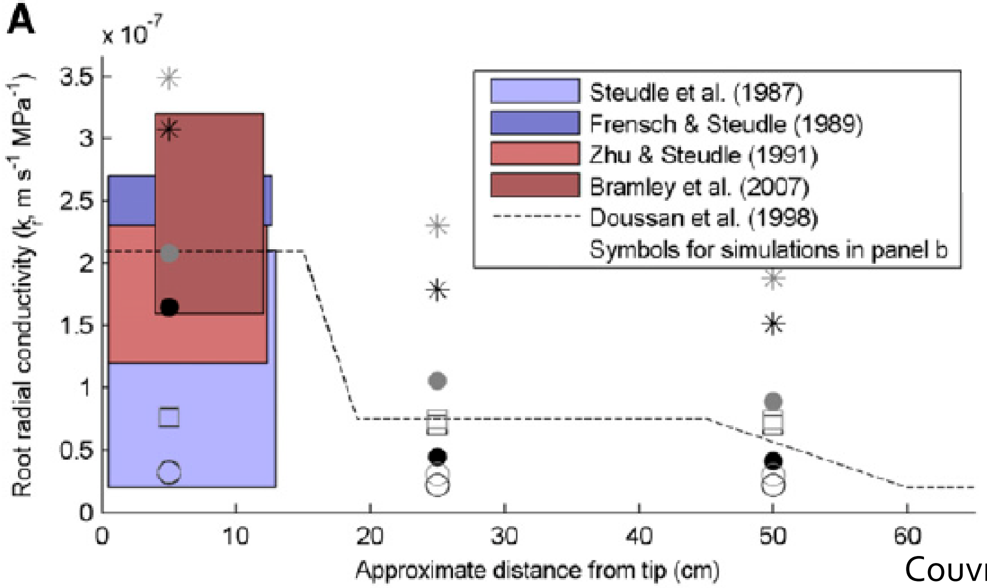
Figures and parameter sets available at `https://figshare.com/collections/CRootBox_parameter_files/3745478`

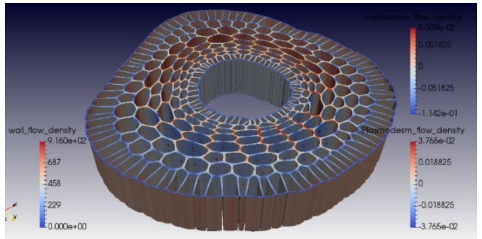
Root hydraulic architecture: radial transport

- Different pathways
- Radial conductivity Kr: function of root anatomy,membrane permeability and maturation
- Short and long term control by plant/environment
- Kr= f(root order and age)





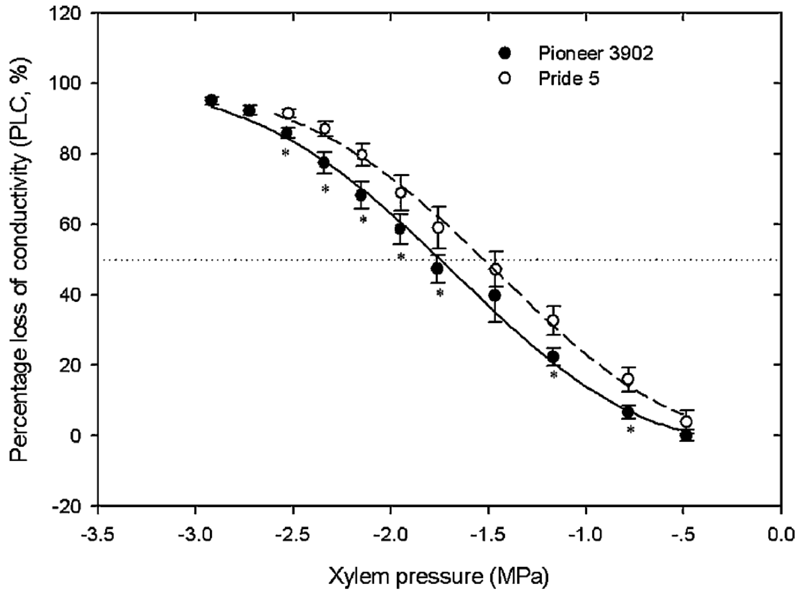




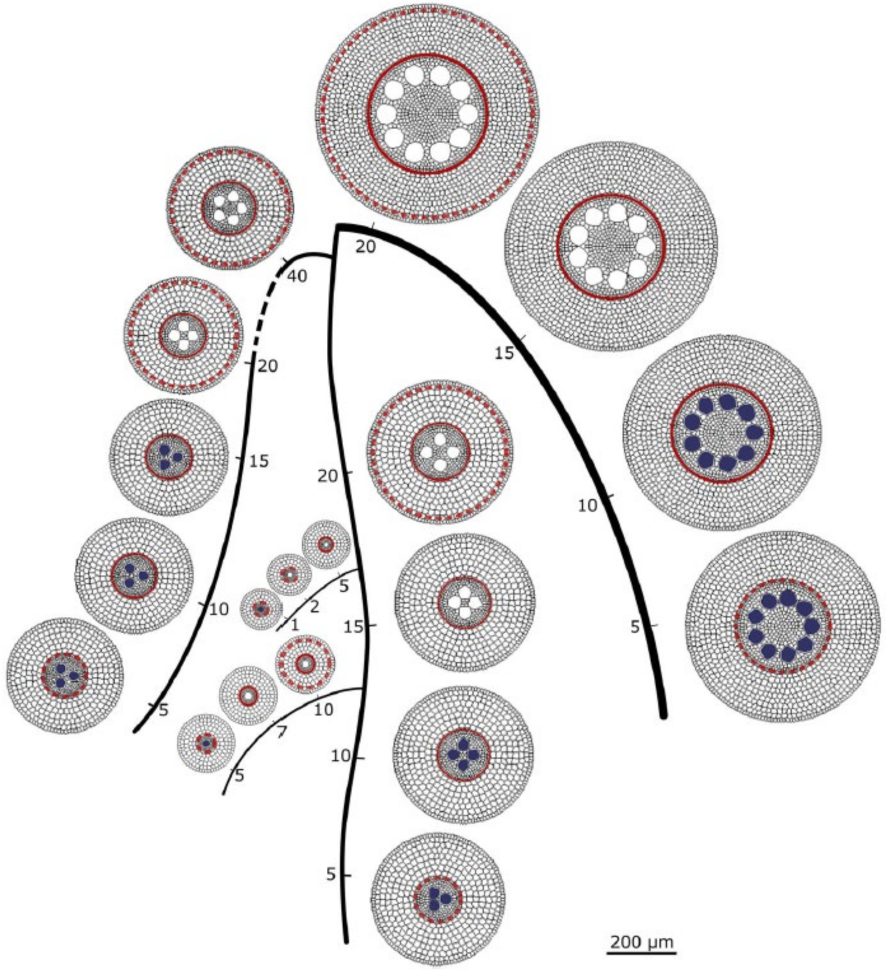
Couvreur et al., PP, 2018

Root hydraulic architecture: xylem flow

- Kx: Axial conductance
- Varies with root diameter, root type and root age
- Embolism



Li et al., 2009

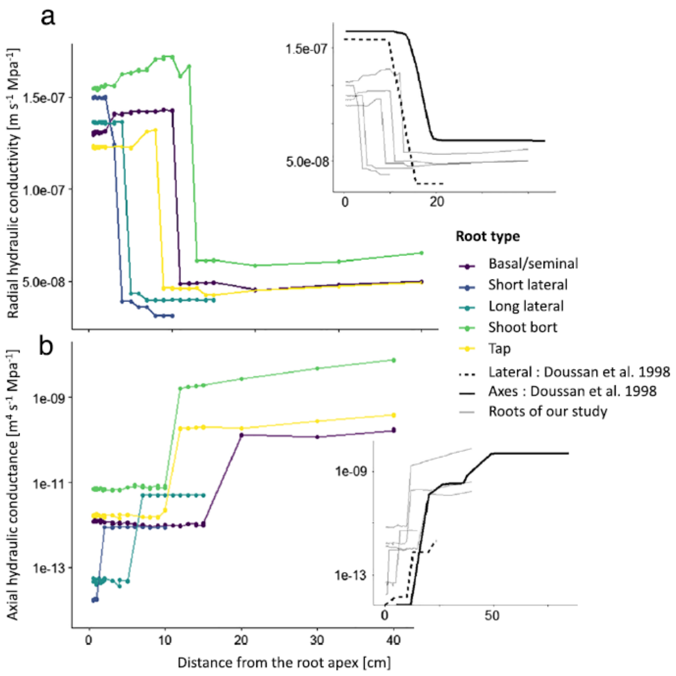


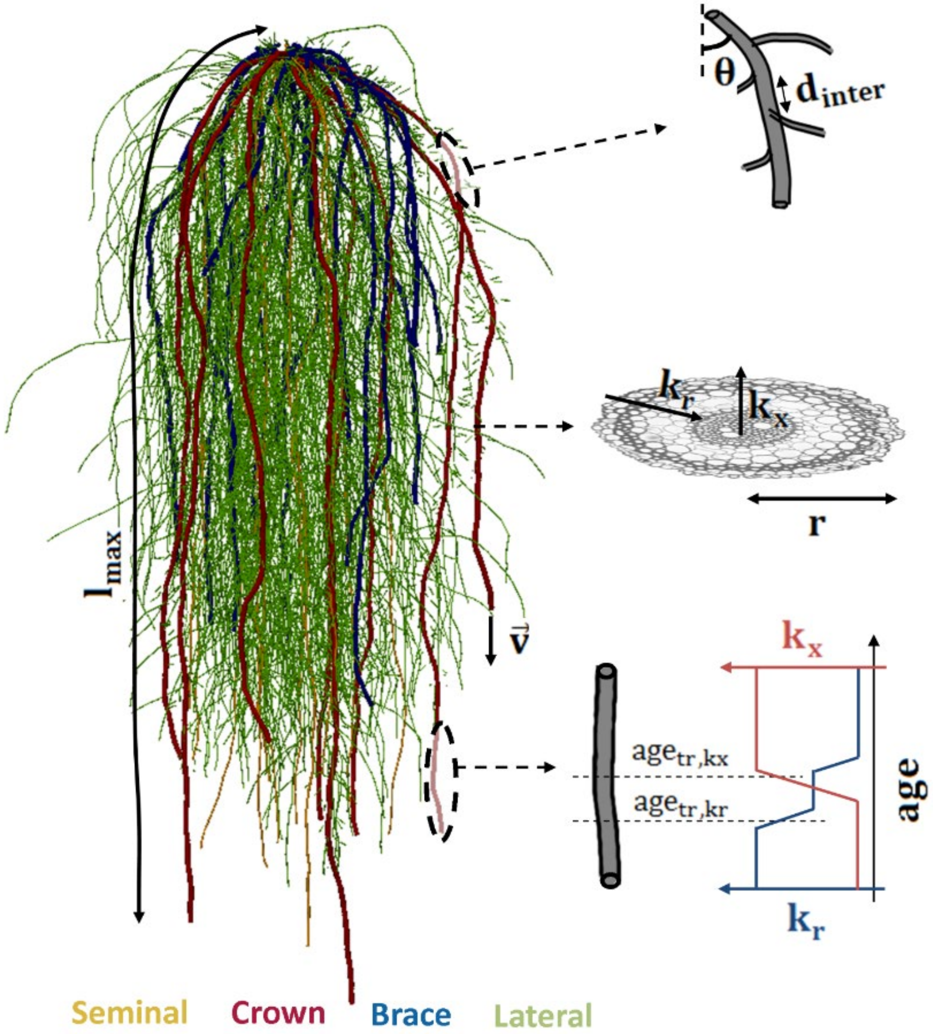
Heymans, 2021

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Root hydraulic architecture

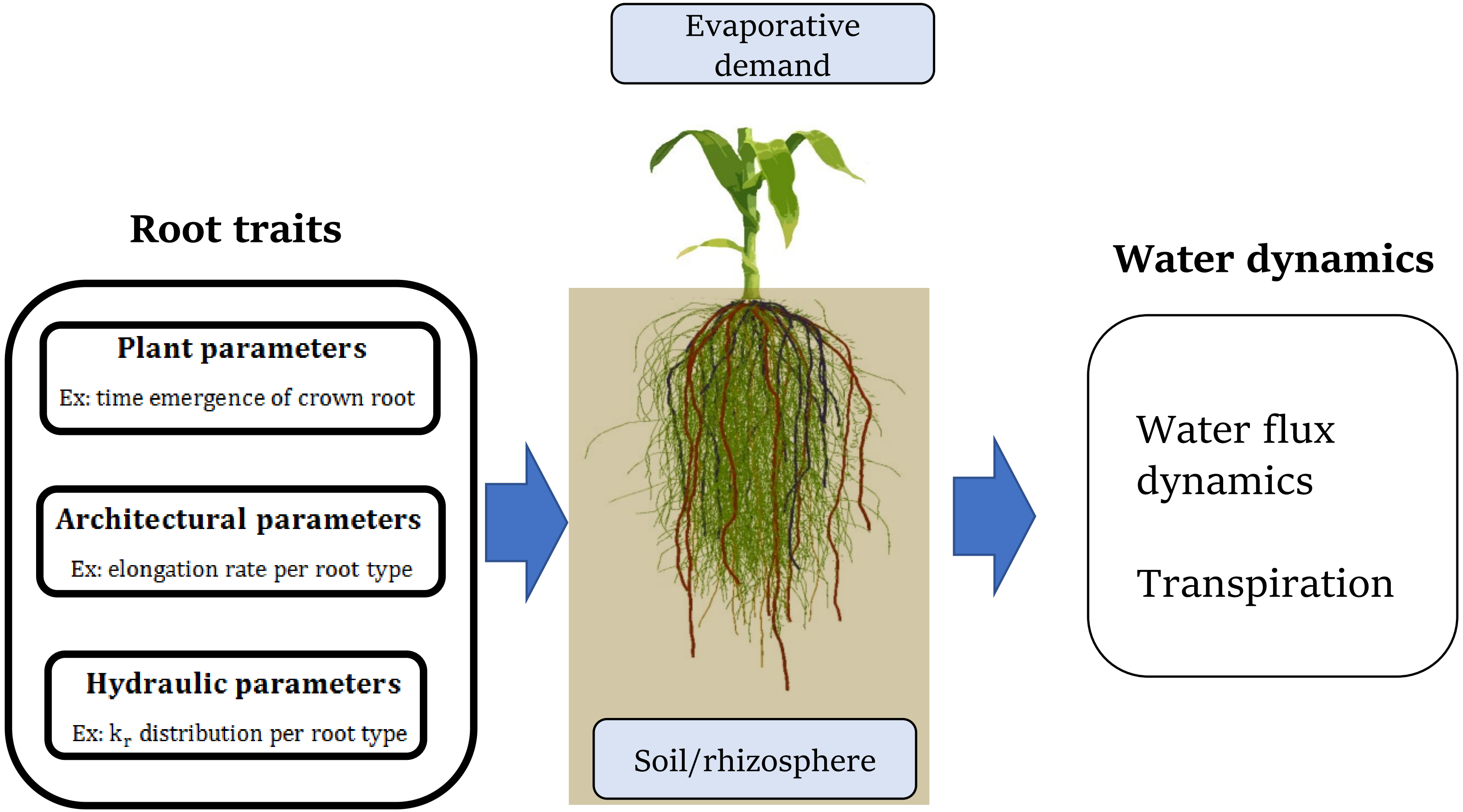
Connected system of root segments with specific hydraulic properties, that develops with time due to age, maturation and plasticity



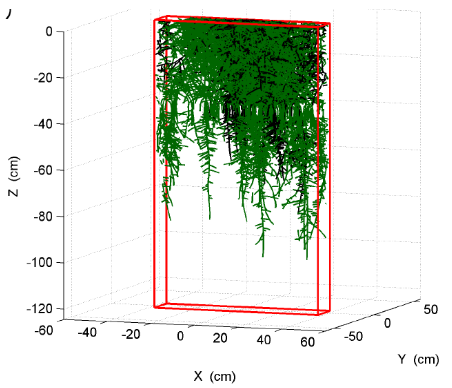


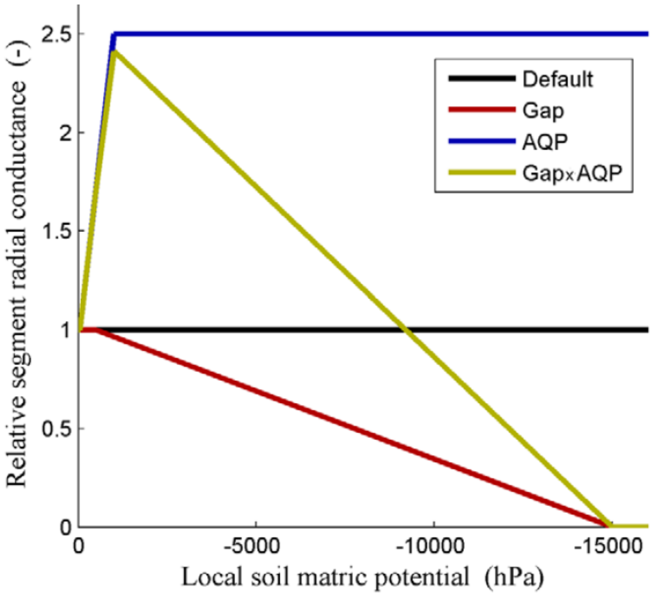
UCLouvain JÜLICH FORSCHUNGSZENTRUM

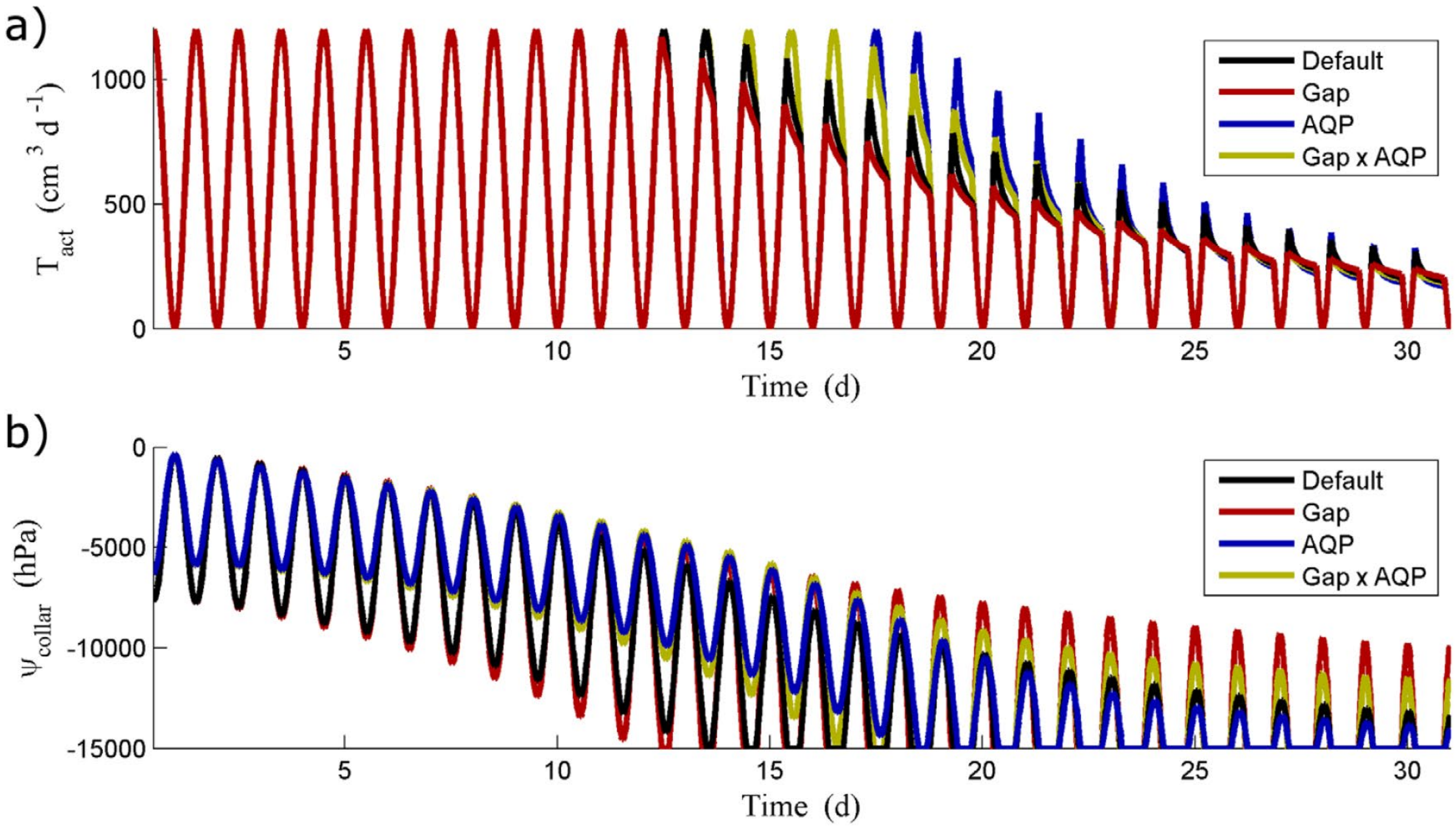
Root system hydraulic architecture



Impact of local root traits on uptake







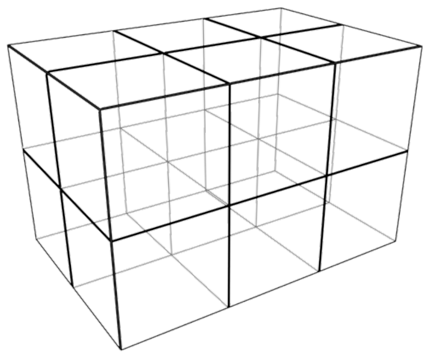
Couvreur et al., 2014

UCLouvain JÜLICH FORSCHUNGSZENTRUM

3D modeling

By combining information on the root hydraulic properties and on the root system architecture, we can explicitly model uptake as a function of soil and root resistances

Soil system



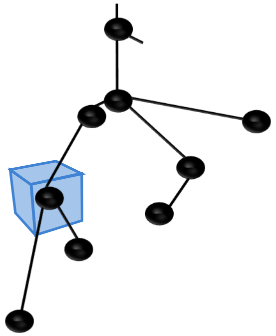
$$\theta_T = R\theta_b + (1-R)\theta_{rh}$$

$$\frac{\partial\theta_T}{\partial t} = R\frac{\partial\theta_b}{\partial t} + (1-R)\frac{1}{\tau}(h - h_{eq}) = \nabla[K\nabla(h+z)] - S$$

R=1 for soil without mucilage

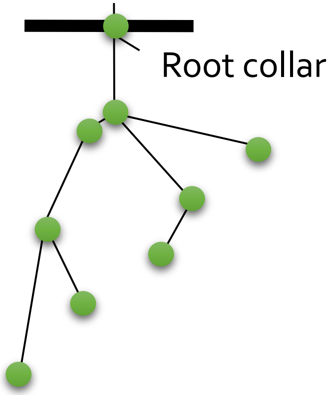
R-SWMS

$$h_s = f(h)$$



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

Root system

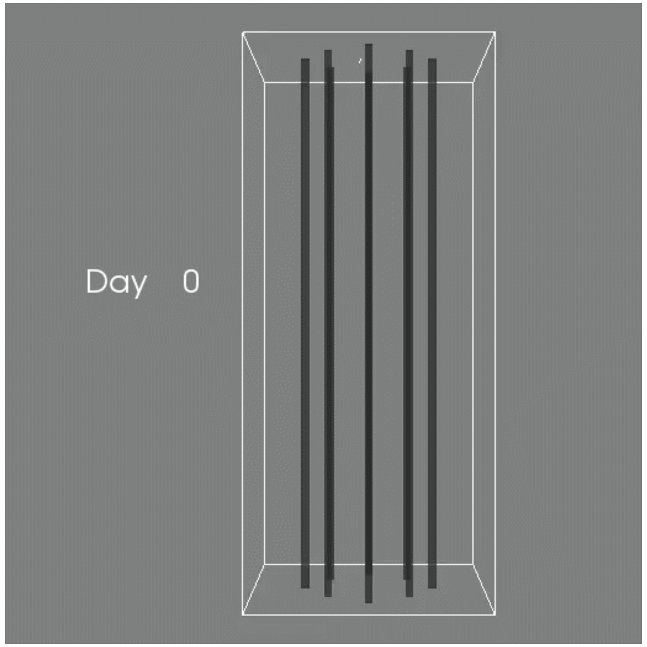


$$J_x = -K_x A_x \frac{\Delta\psi_x(z)}{dl_{seg}}$$

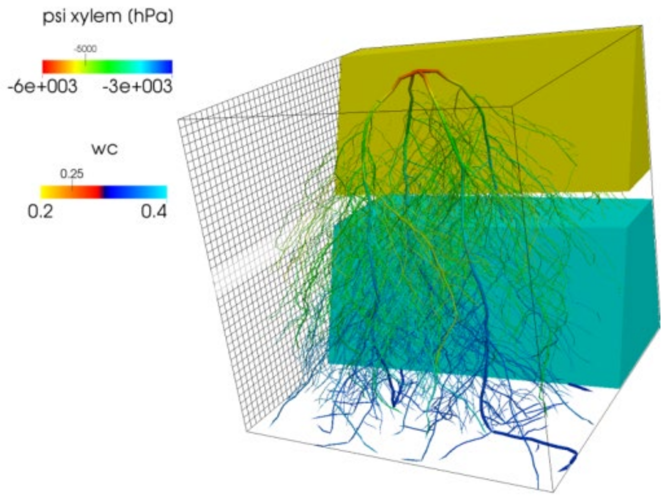
$$J_r = K_r S_r \left[h_s(z) - \psi_x(z)\right]$$

Explicit modeling: FSPM

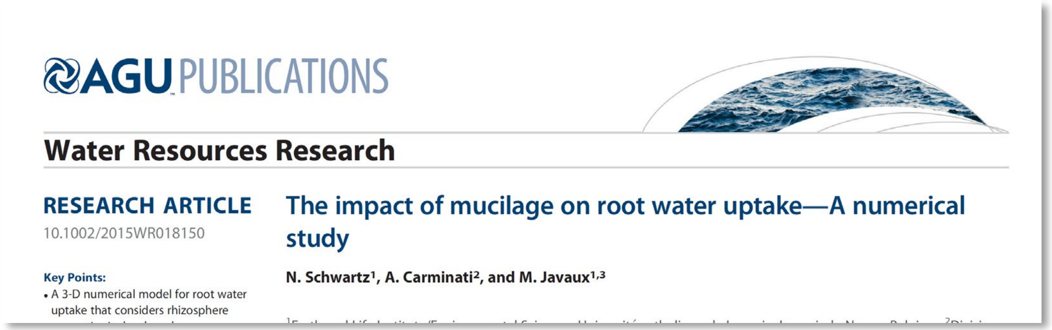
- Soil water flow
- Root water flow
- Soil-root mechanical interactions
- Hormone transport
- Rhizoshere modeling



Landl et al., 2016



Huber et al., 2015


AGU PUBLICATIONS
Water Resources Research
RESEARCH ARTICLE
10.1002/2015WR018150

The impact of mucilage on root water uptake—A numerical study

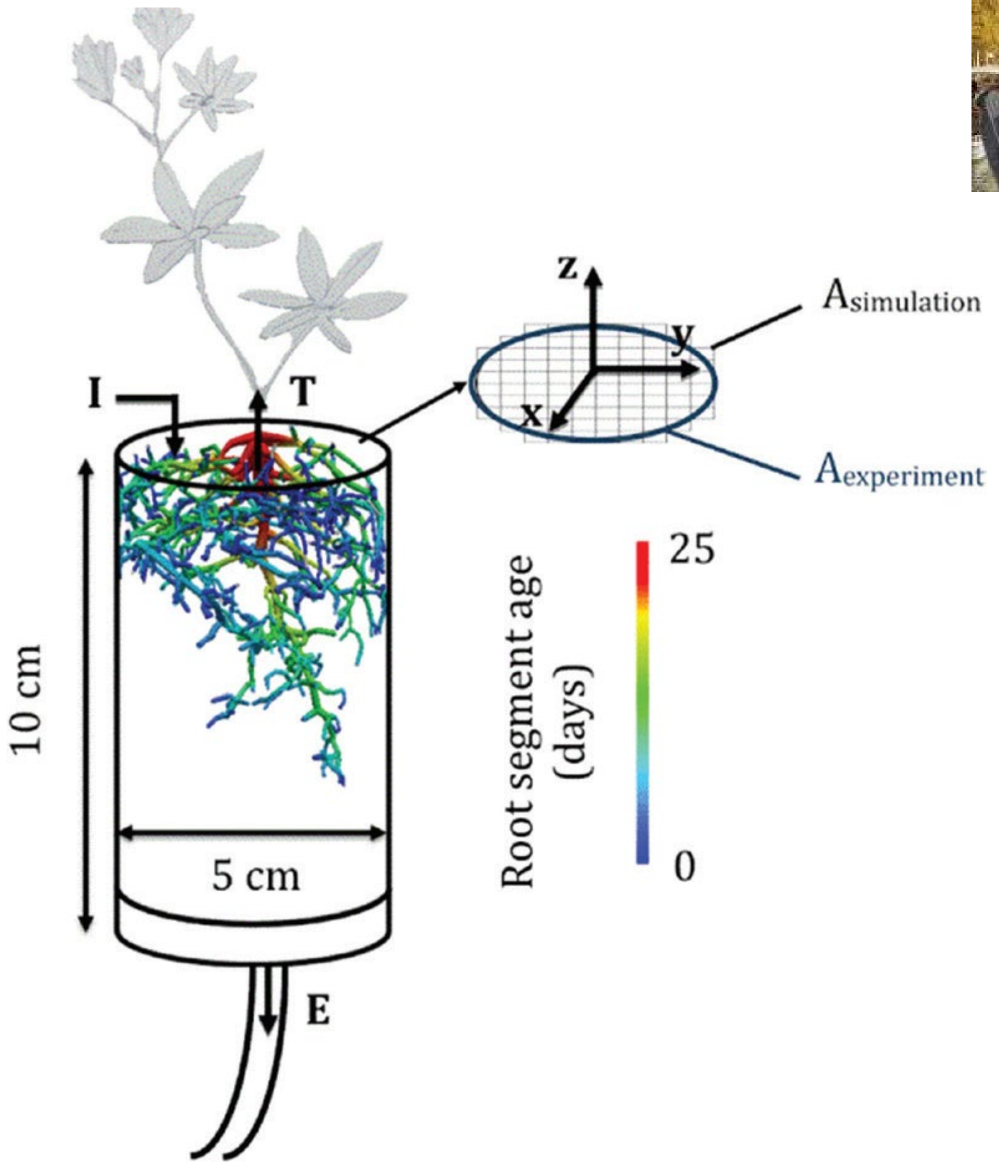
N. Schwartz[1], A. Carminati[2], and M. Javaux[1,3]

Key Points:
- A 3-D numerical model for root water uptake that considers rhizosphere

UCLouvain
JÜLICH FORSCHUNGSZENTRUM

Tracer experiment

- Lupin
- Tracer : Gd-DTPA in water
- Drought experiment ->accumulation
- Scan of the root with MRI
- 3D distribution of accumulation: MRI

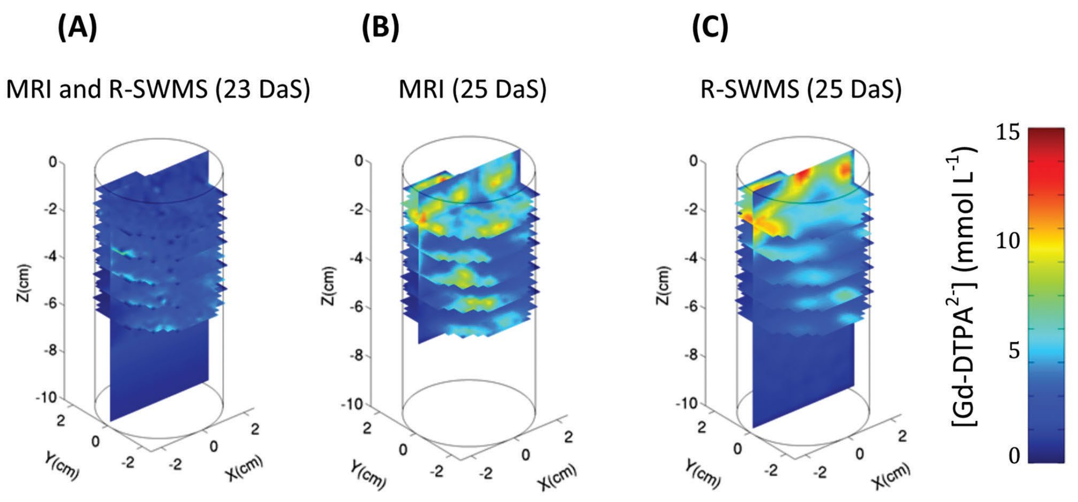


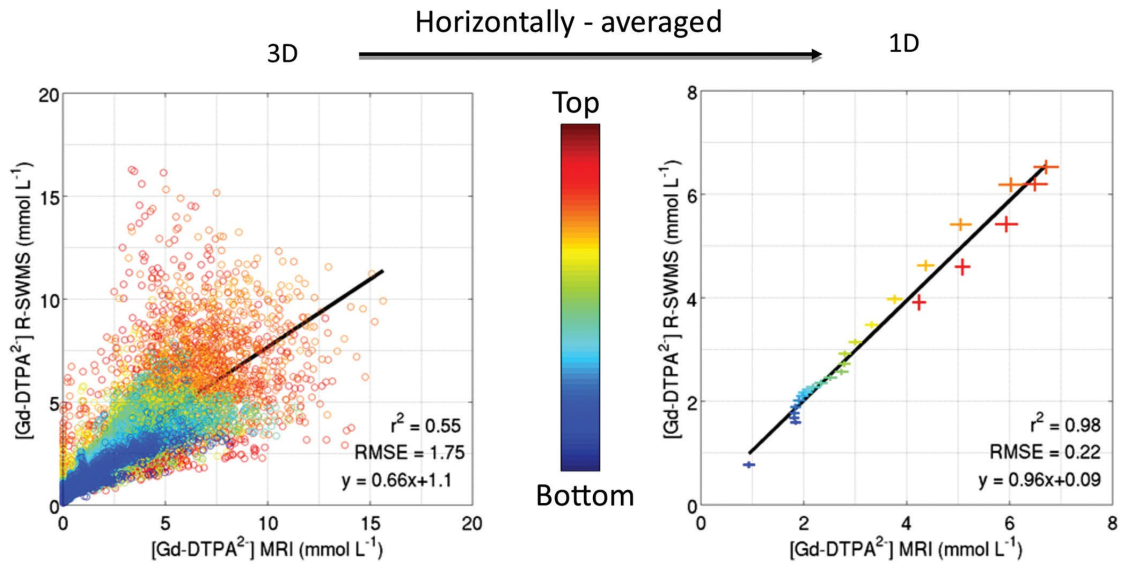
Axelle Koch

3D modeling

Modeling with R-SWMS:

- 3D explicit architectural model (MRI)
- Soil water flow and solute transport
- Measured boundary conditions and soil hydraulic properties
- Hypothesis: no solute uptake



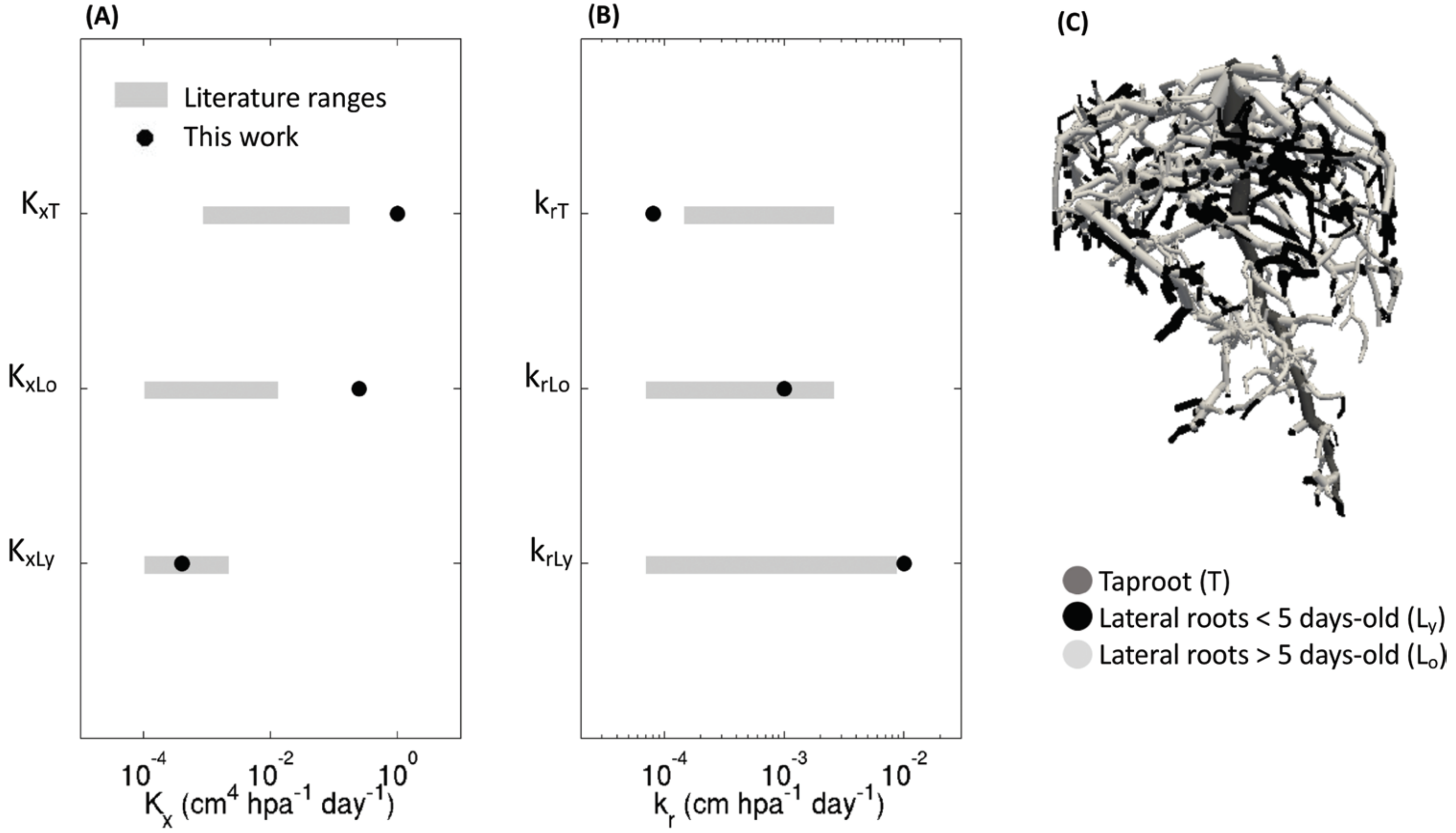


UCLouvain JÜLICH FORSCHUNGSZENTRUM

Koch et al., JExpBot,2109

Inverse modeling

Results: in situ parameterization of root hydraulic properties



Koch et al., JExpBot,2109

Outline

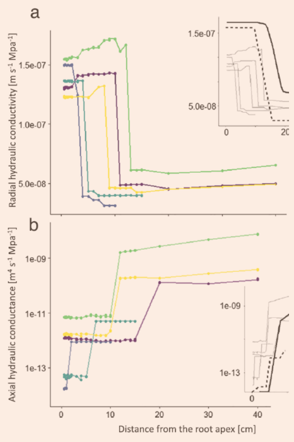
- 3D root system hydraulic architecture:
  - Definition
  - Key traits
- From explicit to implicit RSHA:
  - Root system scale parameters
  - From local traits to root system parameters
- Adding rhizosphere resistance – root activity
- Conclusions

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Modeling approaches : explicit

Root map

Root Hydraulic properties



Explicit 3D modeling (R-SWMS)

Water dynamics

Water flux dynamics

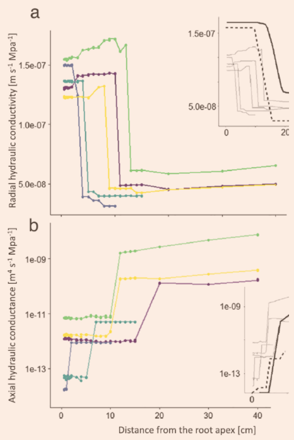
Transpiration

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Modeling approaches : Effective parameterization

Root map

Root Hydraulic properties



Plant effective representation

+ Spatial extent

Water dynamics

Water flux dynamics

Transpiration

Root system-scale hydraulic properties

Questions:

- How to simplify a complex network system?
- How can we represent the ability of a RS to extract water?
- Which traits influence these root system scale properties?

Method:

- Catenary hypothesis, steady-state
- Mass conservation and Thevenin theorem

Root system hydraulic properties

Valentin Couvreur

How can we represent the ability of a RS to extract water?

- Root system conductance (**K_{rs}**)
- Root hydraulic spatial distribution (**SUF/SSF or SUD**)
- Root compensation conductance ≈ Root system conductance

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

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

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

Couvreur et al., 2012

Hydrol. Earth Syst. Sci., 25, 4835–4860, 2021
https://doi.org/10.5194/hess-25-4835-2021

Hydrology and Earth System Sciences

From hydraulic root architecture models to macroscopic representations of root hydraulics in soil water flow and land surface models

Jan Vanderborght[1], Valentin Couvreur[2], Felicien Meunier[3,4], Andrea Schnepf[1], Harry Vereecken[1], Martin Bouda[2,5],

Hydrol. Earth Syst. Sci., 16, 2957–2971, 2012
www.hydrol-earth-syst-sci.net/16/2957/2012/
doi:10.5194/hess-16-2957-2012

Hydrology and Earth System Sciences

A simple three-dimensional macroscopic root water uptake model based on the hydraulic architecture approach

V. Couvreur[1], J. Vanderborght[2], and M. Javaux[1,2]

[1]Earth and Life Institute, Université catholique de Louvain, Croix du Sud, 2, bte L7.05.02, 1348 Louvain-la-Neuve, Belgium
[2]Institute of Bio- und Geosciences, IBG-3: Agrosphere, Forschungszentrum Juelich GmbH, 52425 Juelich, Germany

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Other upscaling approaches

The complex root hydraulic architecture is summarized into 'effective parameters' that exactly represent its hydraulic behavior

- H control (Couvreur et al., HESS, 2012):

$$T_a = K_{root}\left(\overline{\psi}_s - \psi_{leaf}\right)$$

Root conductance

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

Spatial root property distribution

- H+C control (Huber et al., PLSO, 2015):

Fraction of roots in the dry soil

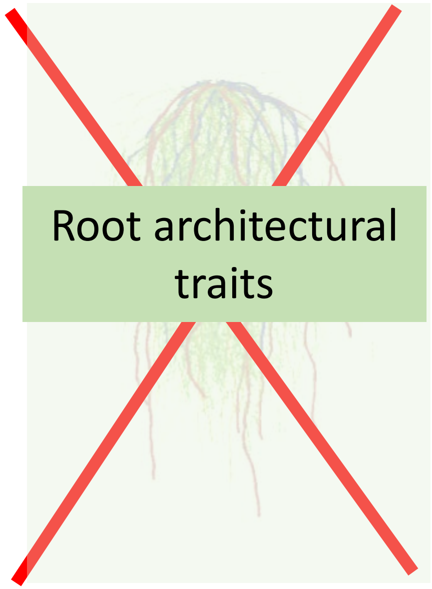
$$T_{act} = T_{pot}\, exp\left[\frac{-s_c f_{dry} a^*}{(1-f_{dry})K_{root}}\left|1-\frac{\psi_{lim}}{\psi_{leaf}}\right| exp\left(s_p\left|\psi_{leaf}\right|\right)\right]$$

- C control

(Huber et al., PLSO, 2015):

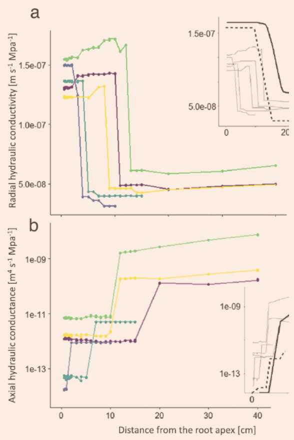
$$T_{act} = T_{pot}\, exp\left[\frac{-s_c f_{dry} a^*}{(1-f_{dry})K_{root}}\right]$$

Modeling approaches : Effective parameterization



Root architectural traits

Root Hydraulic properties



Meunier etal., 2017

Plant effective representation

+ Spatial extent

Water dynamics

Water flux dynamics

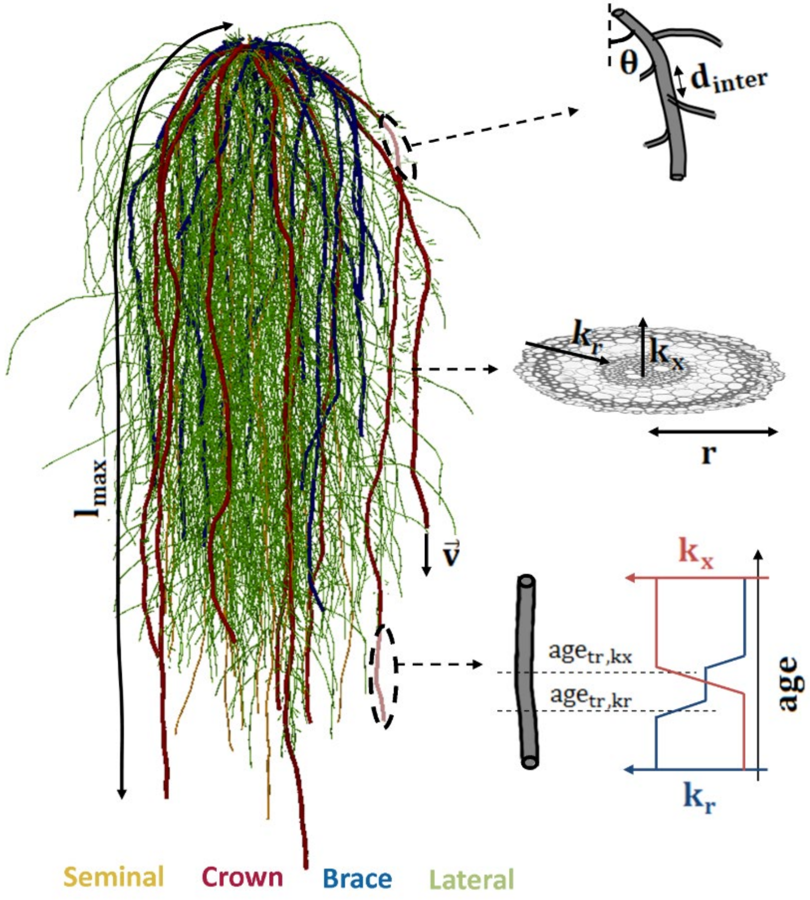
Transpiration

From traits to RS hydraulic properties

- Architectural and hydraulic traits control K_{rs} and SUF*:*
  - Radial conductivity, and its evolution with root segment age
  - Axial conductance, and its evolution with root segment age
  - Distance between laterals, number of primary roots

- Architectural traits control root spatial invasion (V_{root}):
  - Growth rate
  - Lateral angles
  - Number of primary roots

- **Challenge**: finding an analytical solution, which predicts directly the root ability to extract water and its extent based on local traits without the need of an explicit architecture



From root traits to root system properties

Félicien Meunier

Strategy:

- Develop analytical solution of the water flow equations for root branches, function of root traits
- To combine root branches into an 'ideal' implicit root system and estimate plant scale parameters

Hydrol. Earth Syst. Sci., 21, 6519–6540, 2017
https://doi.org/10.5194/hess-21-6519-2017

Hydrology and Earth System Sciences
Open Access
EGU

Water movement through plant roots – exact solutions of the water flow equation in roots with linear or exponential piecewise hydraulic properties

Félicien Meunier[1], Valentin Couvreur[2], Xavier Draye[2], Mohsen Zarebanadkouki[3], Jan Vanderborght[4,5], and Mathieu Javaux[1,4]

[1]Earth and Life Institute – Environment, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[2]Earth and Life Institute – Agronomy, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[3]Division of Soil Physics, University of Bayreuth, Germany
[4]Forschungszentrum Juelich GmbH, Agrosphere (IBG-3), Juelich, Germany
[5]Division of Soil and Water Management, KU Leuven, Leuven, Belgium

Applied Mathematical Modelling 52 (2017) 648–663

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

ELSEVIER

A hybrid analytical-numerical method for solving water flow equations in root hydraulic architectures

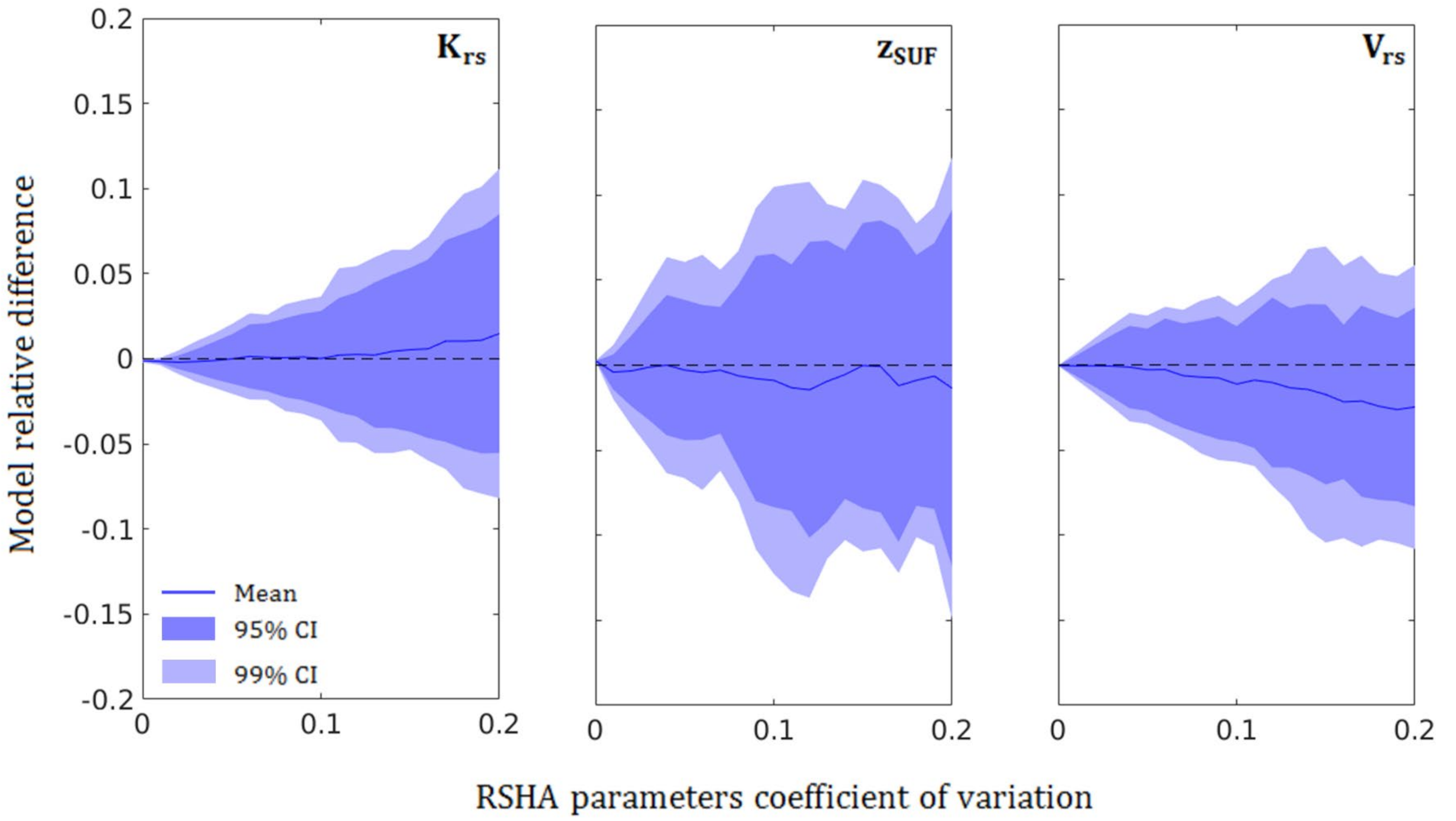
CrossMark

Félicien Meunier[a,*], Xavier Draye[b], Jan Vanderborght[c,d], Mathieu Javaux[a,d], Valentin Couvreur[b]

[a] Earth and Life Institute-Environnement, Université catholique de Louvain, Belgium
[b] Earth and Life Institute-Agronomy, Université catholique de Louvain, Belgium
[c] Division of soil and water management, Katholieke Universiteit Leuven, Belgium
[d] Forschungszentrum Juelich GmbH, Agrosphere Institute, IBG-3, Juelich, Germany

Meunier et al, 2017ab

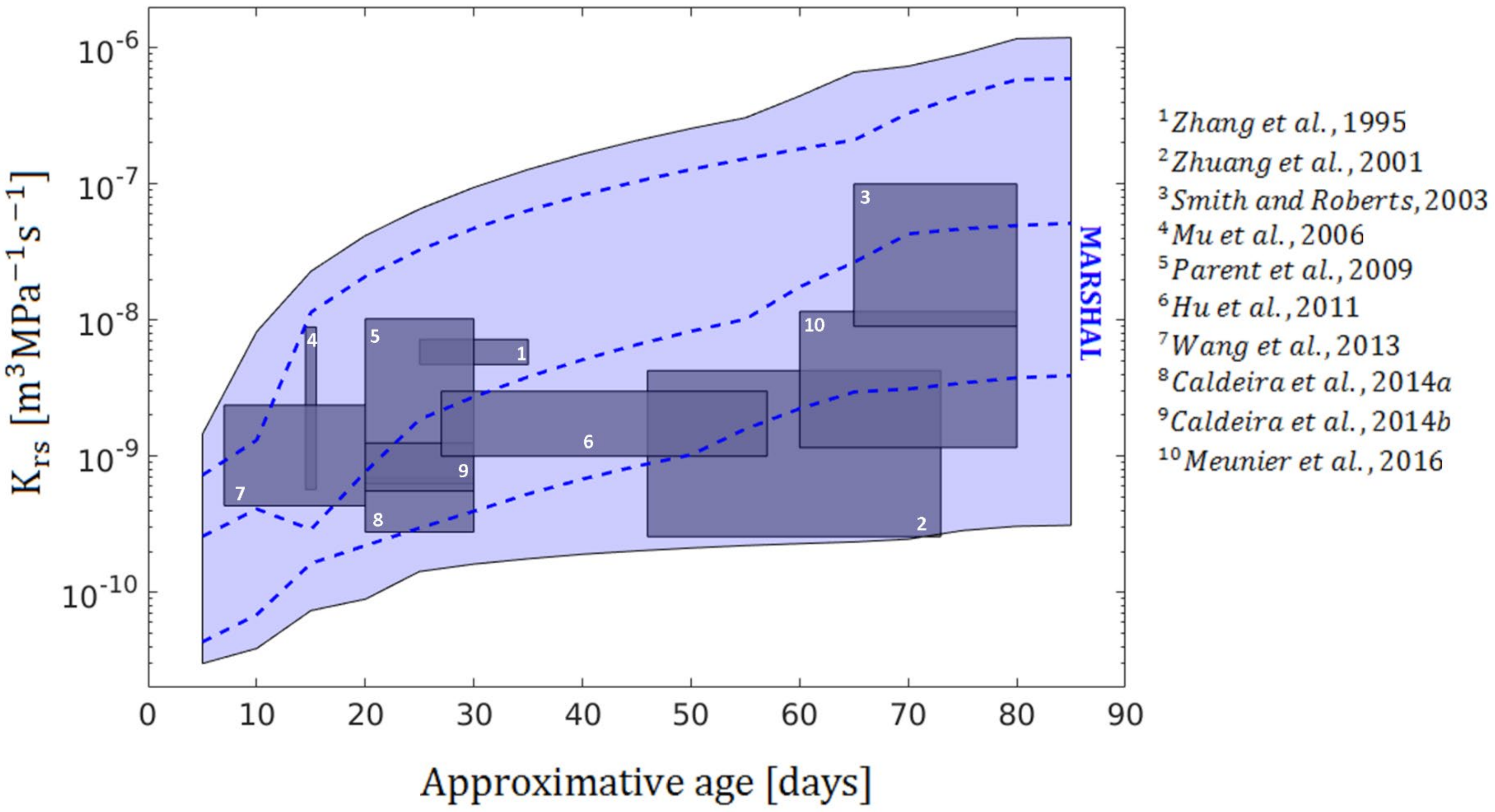
Implicit Root system architecture



Blue envelope: difference betwen architectural explicit model and Marshal

Meunier et al, 2019

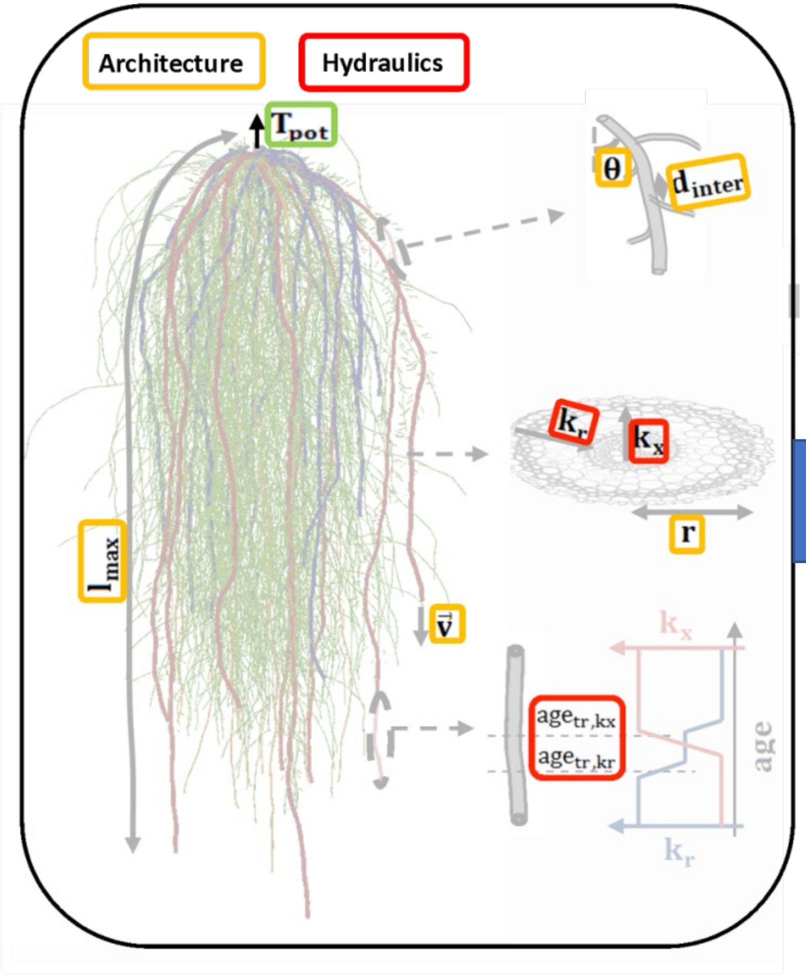
Root conductance estimation



We can estimate root conductances based on local traits!

Meunier et al, 2019

From root traits to root system properties



MARSHAL

$$K_{\mathrm{rs},i} = k_x(l_i)\frac{\begin{bmatrix}\left(-K_{\mathrm{rs},i-1}f_{2,i}(l_{i-1})+f'_{2,i}(l_{i-1})k_x(l_{i-1})\right)f'_{1,i}(l_i)\\+\left(K_{\mathrm{rs},i-1}f_{1,i}(l_{i-1})-f'_{1,i}(l_{i-1})k_x(l_{i-1})\right)f'_{2,i}(l_i)\end{bmatrix}}{\begin{bmatrix}K_{\mathrm{rs},i-1}f_{1,i}(l_{i-1})f_{2,i}(l_i)-K_{\mathrm{rs},i-1}f_{1,i}(l_i)f_{2,i}(l_{i-1})\\-f'_{1,i}(l_{i-1})f_{2,i}(l_i)k_x(l_{i-1})+f_{1,i}(l_i)f'_{2,i}(l_{i-1})k_x(l_{i-1})\end{bmatrix}}$$

$$\mathrm{SUD}_i(z) = \frac{2\pi r k_r(z)}{k_x(l_i)}\frac{\begin{bmatrix}\left(-K_{\mathrm{rs},i-1}f_{2,i}(l_{i-1})+f'_{2,i}(l_{i-1})k_x(l_{i-1})\right)f_{1,i}(z)\\+\left(K_{\mathrm{rs},i-1}f_{1,i}(l_{i-1})-f'_{1,i}(l_{i-1})k_x(l_{i-1})\right)f_{2,i}(z)\end{bmatrix}}{\begin{bmatrix}\left(-K_{\mathrm{rs},i-1}f_{2,i}(l_{i-1})+f'_{2,i}(l_{i-1})k_x(l_{i-1})\right)f'_{1,i}(l_i)\\+\left(K_{\mathrm{rs},i-1}f_{1,i}(l_{i-1})-f'_{1,i}(l_{i-1})k_x(l_{i-1})\right)f'_{2,i}(l_i)\end{bmatrix}}$$

K_{rs}

Standard Uptake Fraction

Meunier et al, 2017ab

https://plantmodelling.shinyapps.io/marshal/

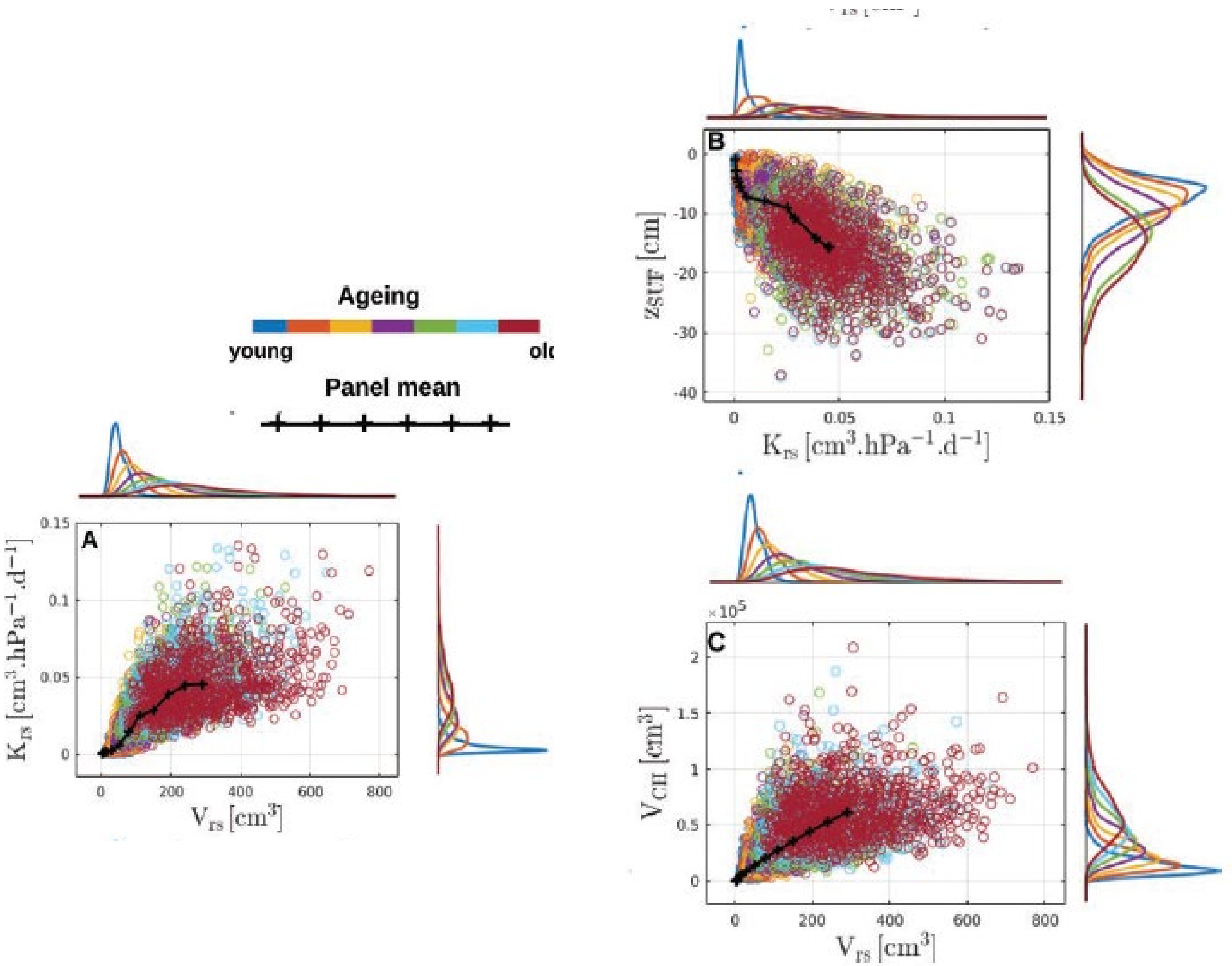
Scan me

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Defining new ideotypes for drought tolerance

- Generation of 10000 « genotypes »

- Investigation of how root conductane and invasion evolve with root age



UCLouvain JÜLICH FORSCHUNGSZENTRUM

Outline

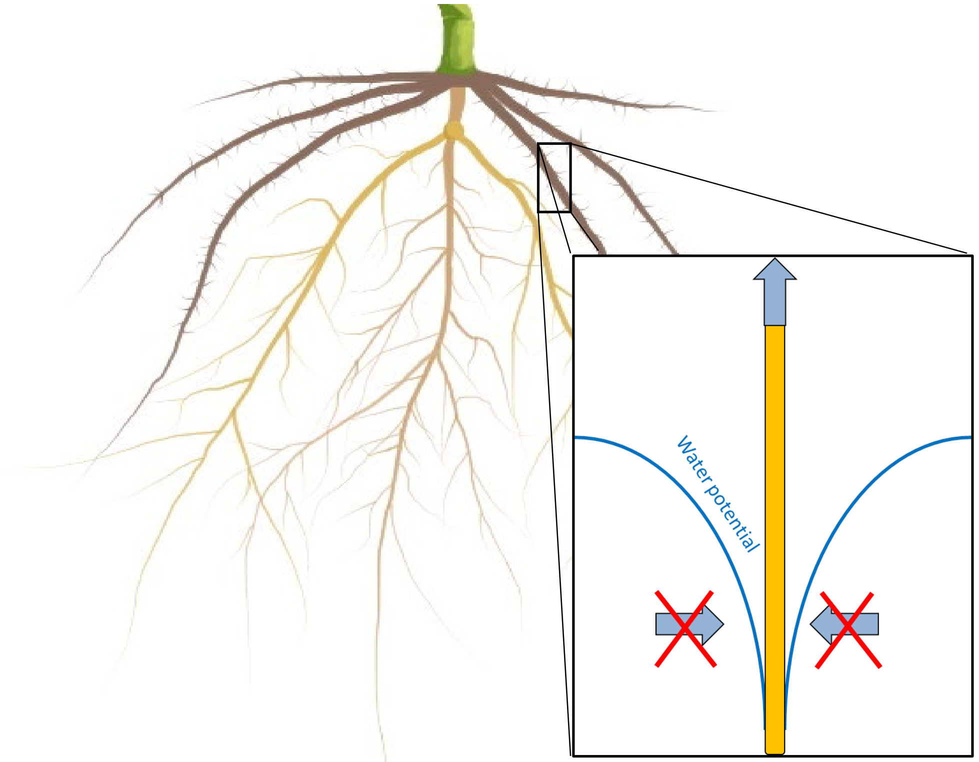
- 3D root system hydraulic architecture:
  - Definition
  - Key traits
- From explicit to implicit RSHA:
  - Root system scale parameters (Couvreur)
  - From local traits to root system parameters
- Adding rhizosphere resistance – root activity
- Conclusions

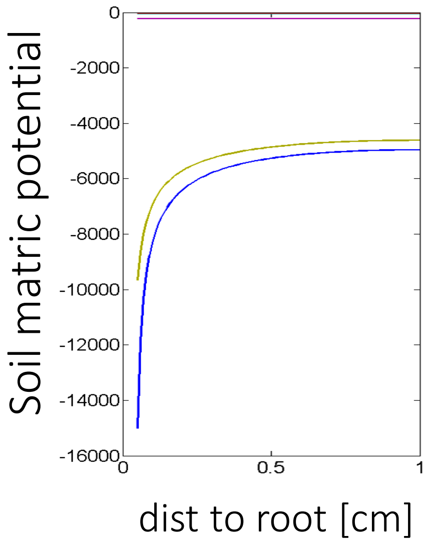
Rhizosphere resistance

- Function of soil/rhizosphere hydraulic properties
- Function of transpiration flux and bulk water potential
- Function of root length/surface

$$q = -k(\psi)\frac{\partial \psi}{\partial r} = -\frac{\partial \phi}{\partial r} \qquad \phi(\psi) = \int_{-\infty}^{\psi} k(x)\,dx$$

$$\phi_{soil,root} = -\frac{T}{2\pi r L}\left(\frac{r_0}{2} - r_0 r_2^2 \frac{\ln(r_2/r_0)}{r_2^2 - r_0^2}\right) + \left(\phi_{soil,bulk}\right)$$



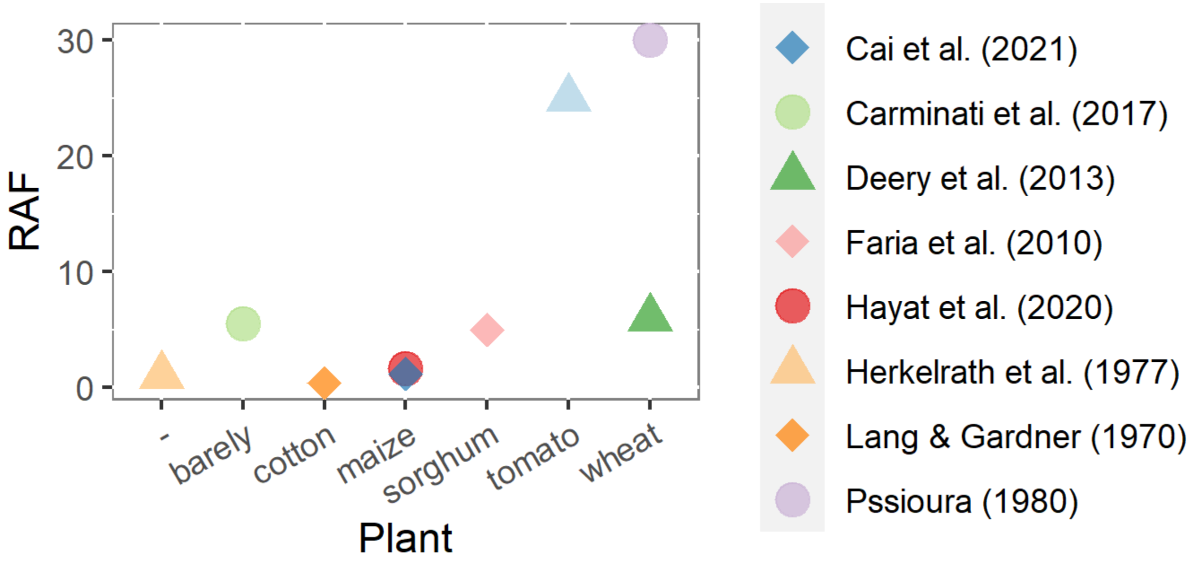


(Gardner, 1960, Schroeder et al, 2007;2008)

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Root activity

- Active fraction of the root system
- Key factor for rhizosphere conductance
- Generally (very) low
- Most roots are ‘active’
- Root active fraction (RAF) : factor in root length-based models



Objectives

- Provide a new definition of root activity
- Quantify the influecne of different soil and root properties on root active fraction
- Determine ‘realsitic’ root active fraction

Ali Mehmandoost Kotlar

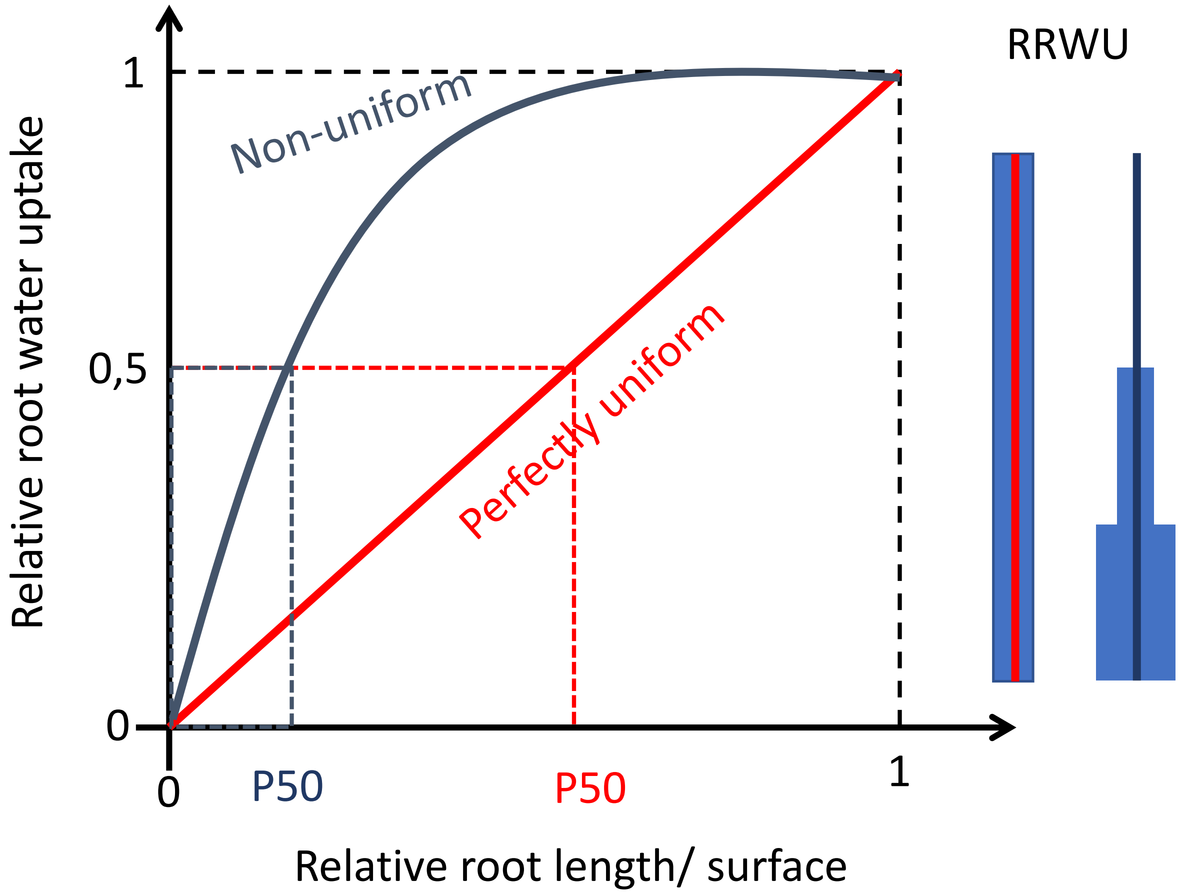
UCLouvain JÜLICH FORSCHUNGSZENTRUM

Root water uptake distribution

P50 of the RRWA: good estimate of RWU uniformity

Simulation exercise:

How does P50 change with root and soil hydraulic property distribution?



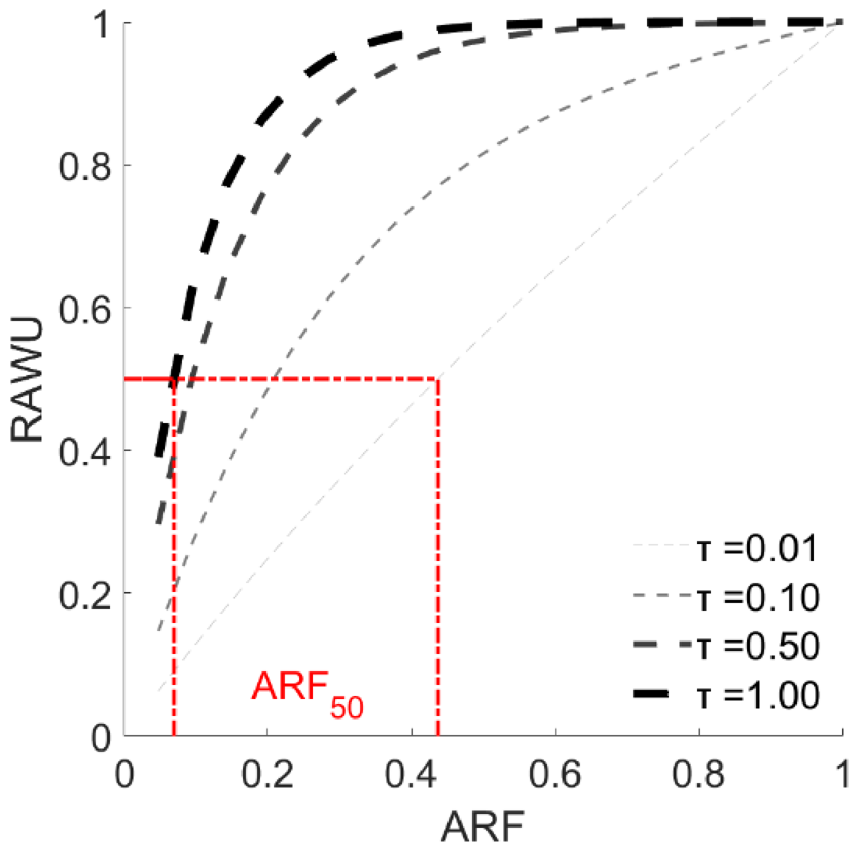
UCLouvain JÜLICH FORSCHUNGSZENTRUM

Single homogeneous root

- Hydraulic properties of single root affect RWU
- Meunier et al. (2017), Standard uptake fraction

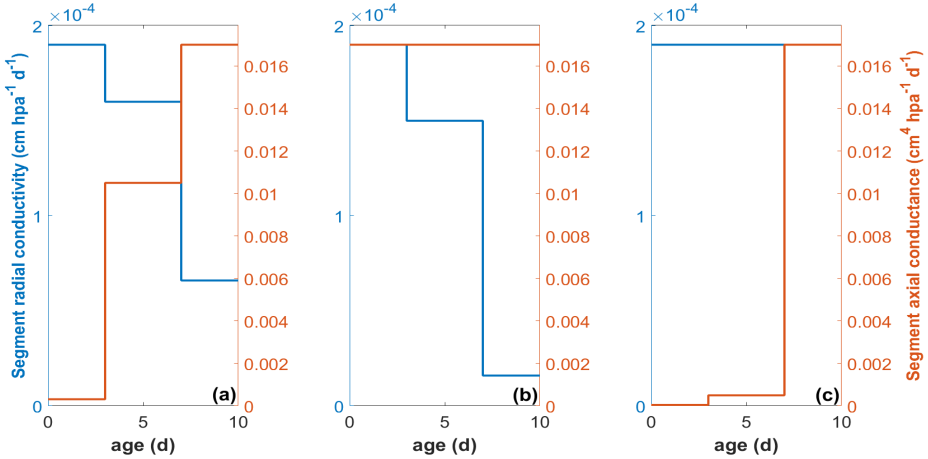
$$SUD(z, l_{root}) \simeq \frac{1}{l_{root}}\left(1 + \frac{(\tau z)^2}{2}\right)$$

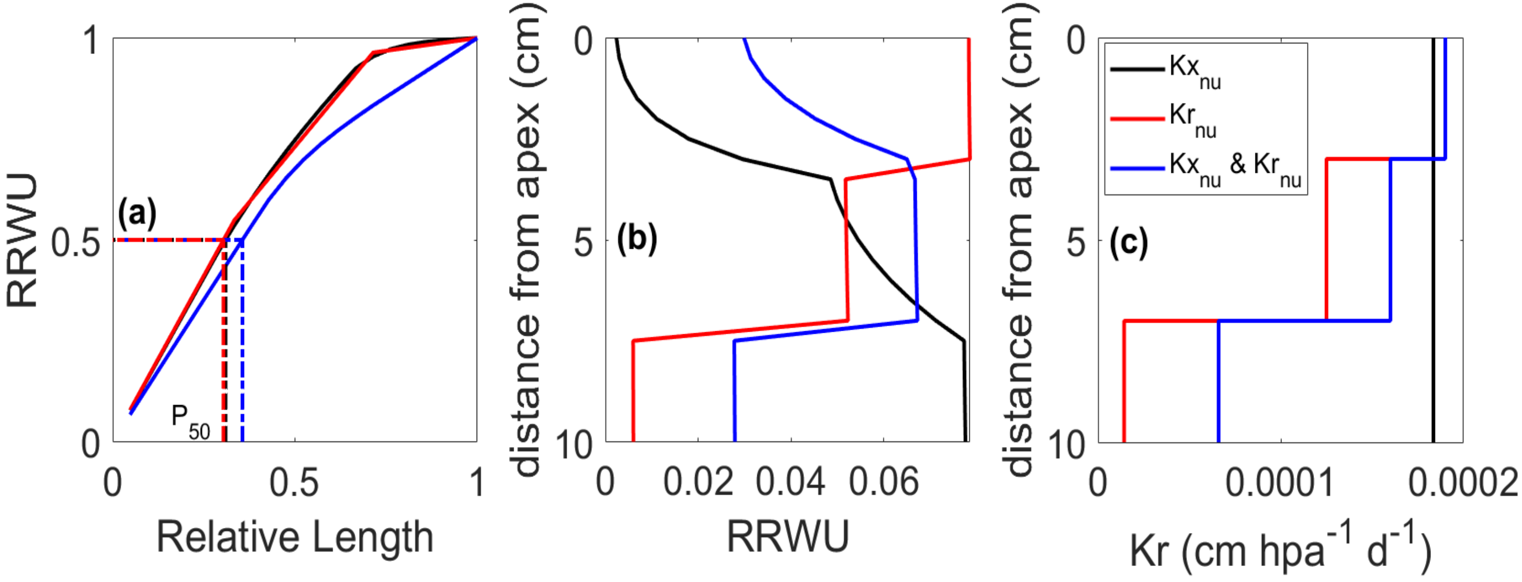
$$\tau = \sqrt{\frac{2\pi\, \mathrm{r k_r}}{\mathrm{k_x}}}\ [\mathrm{L}^{-1}]$$



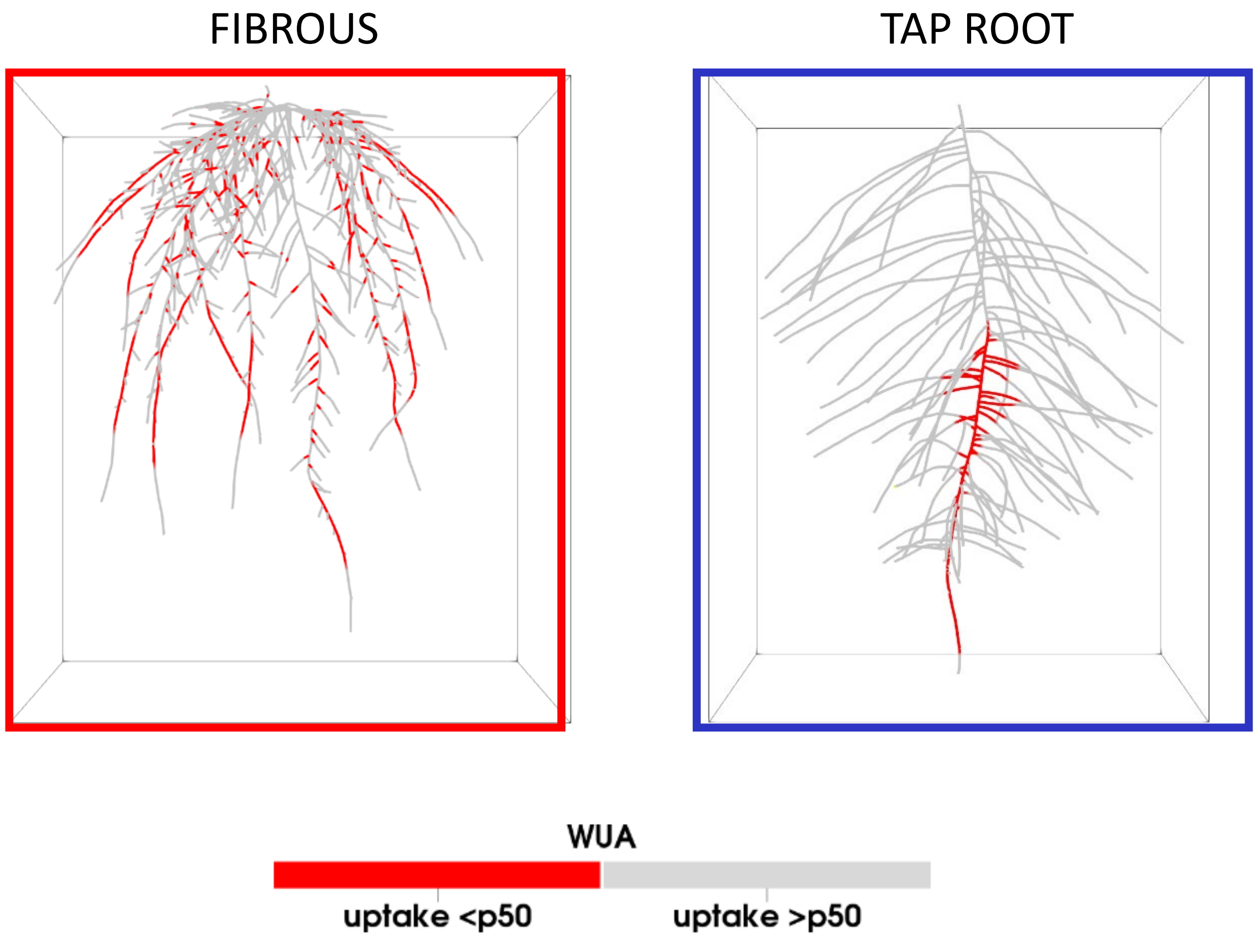
Single heterogeneous root system

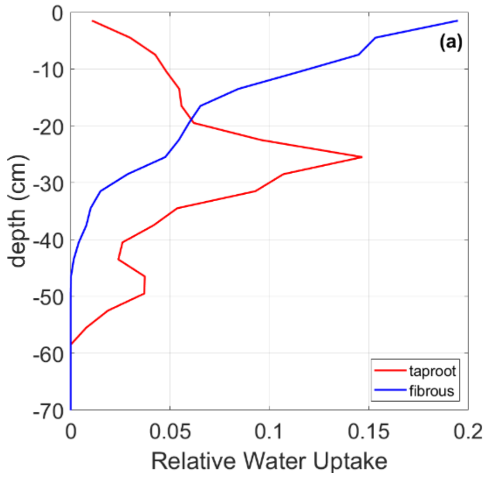
Roots with three « zones »

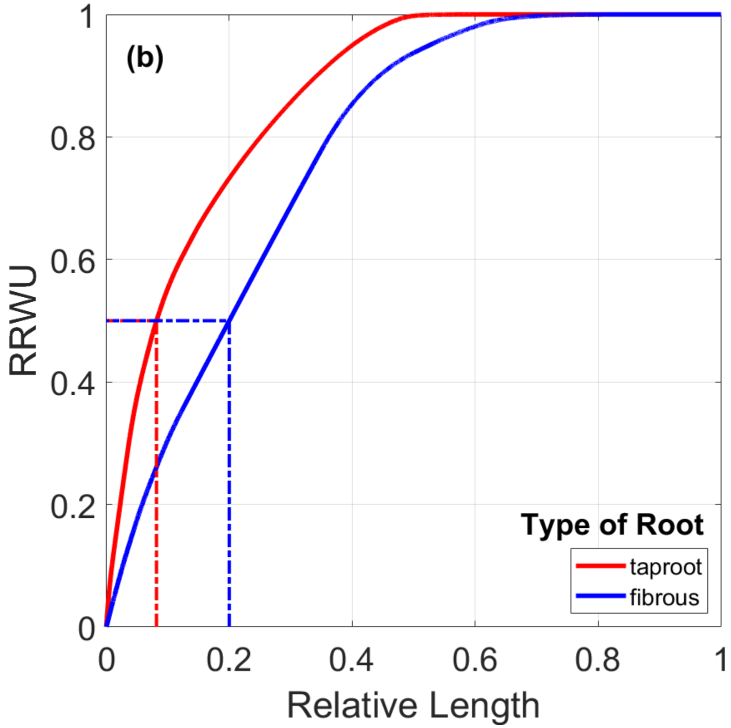




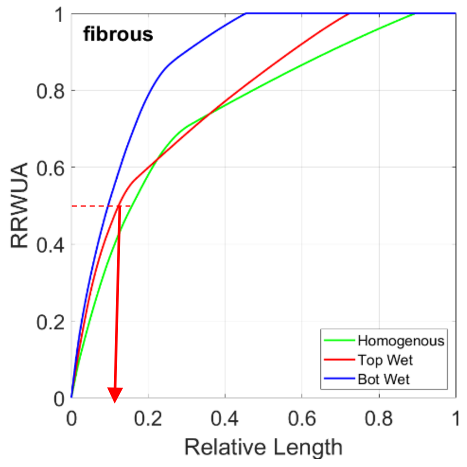
Root system architecture

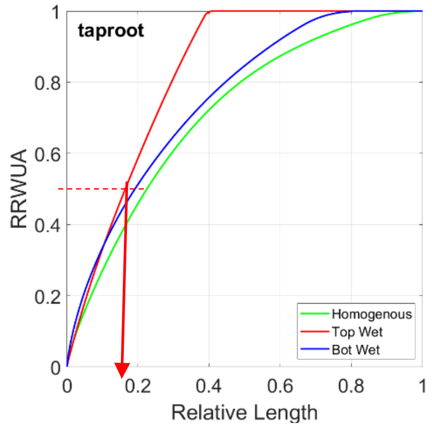


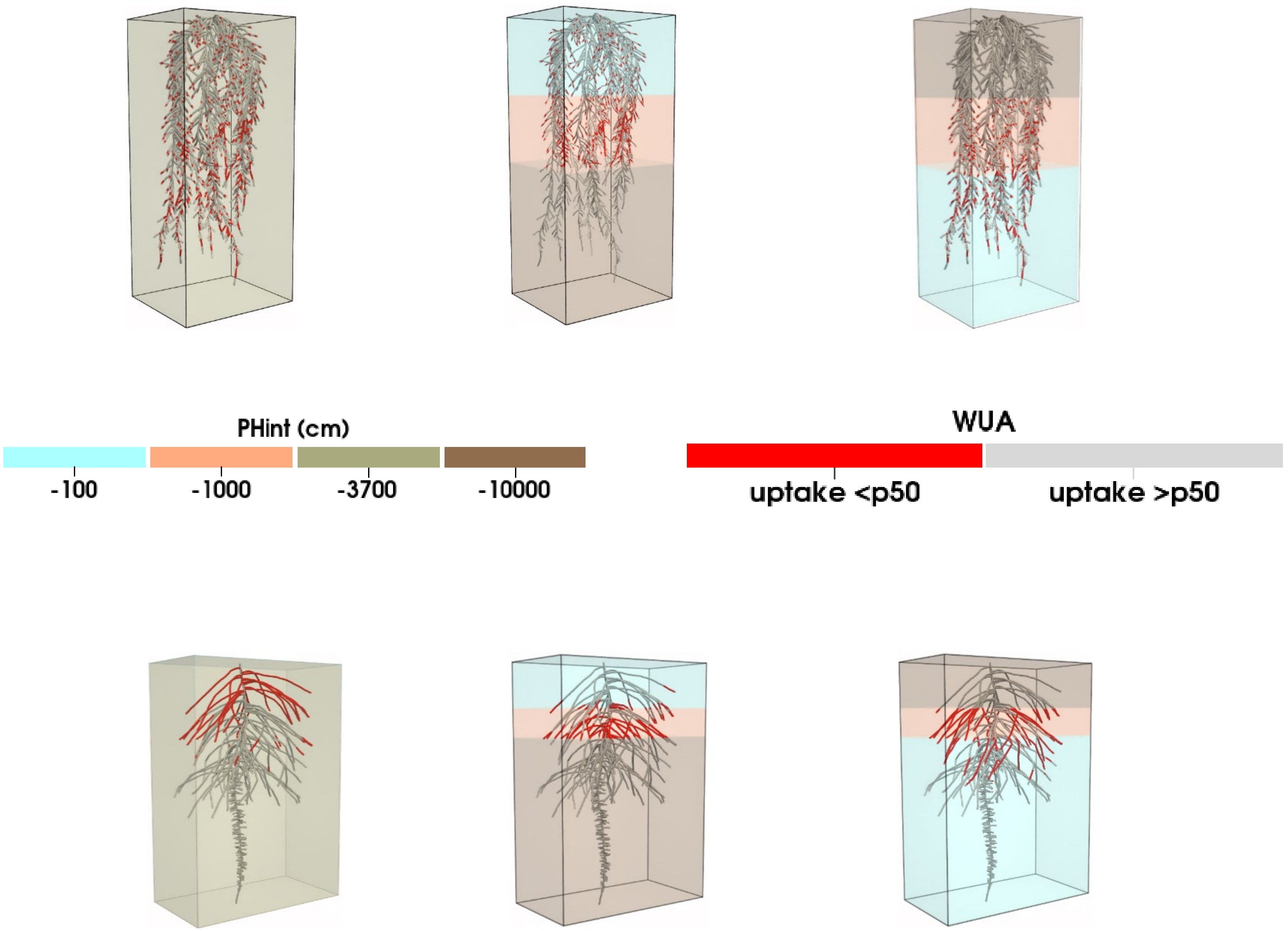




Root system architecture (heterogeneous soil)

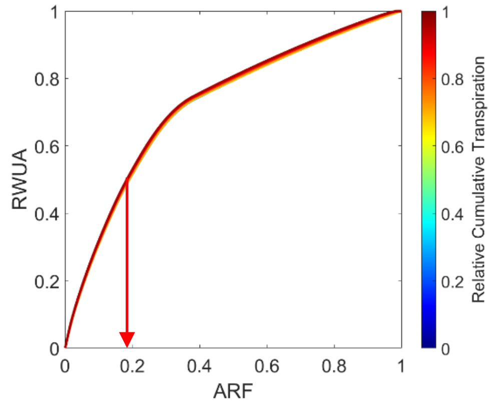


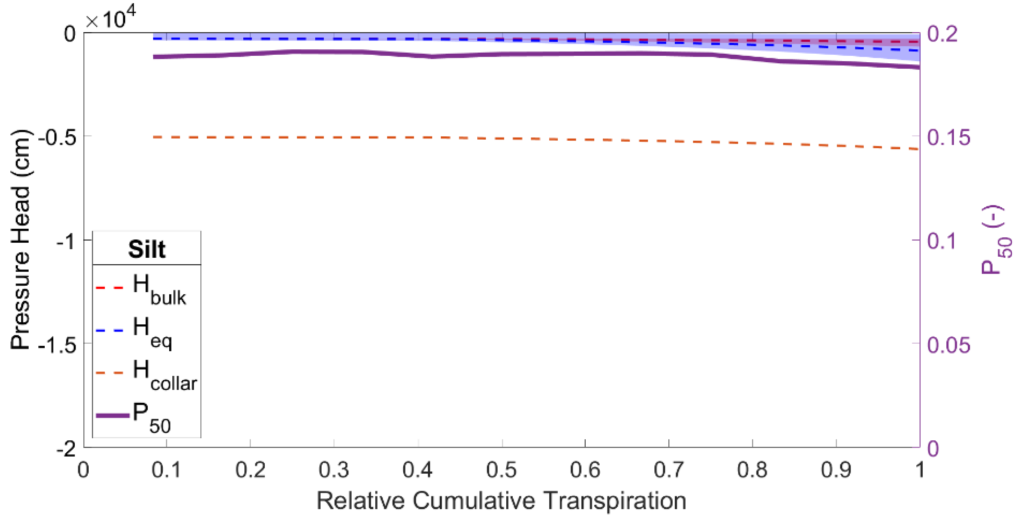


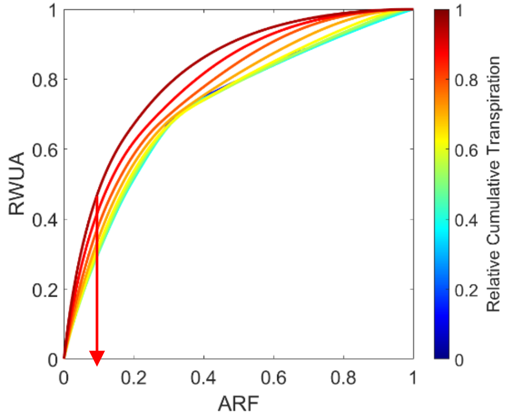


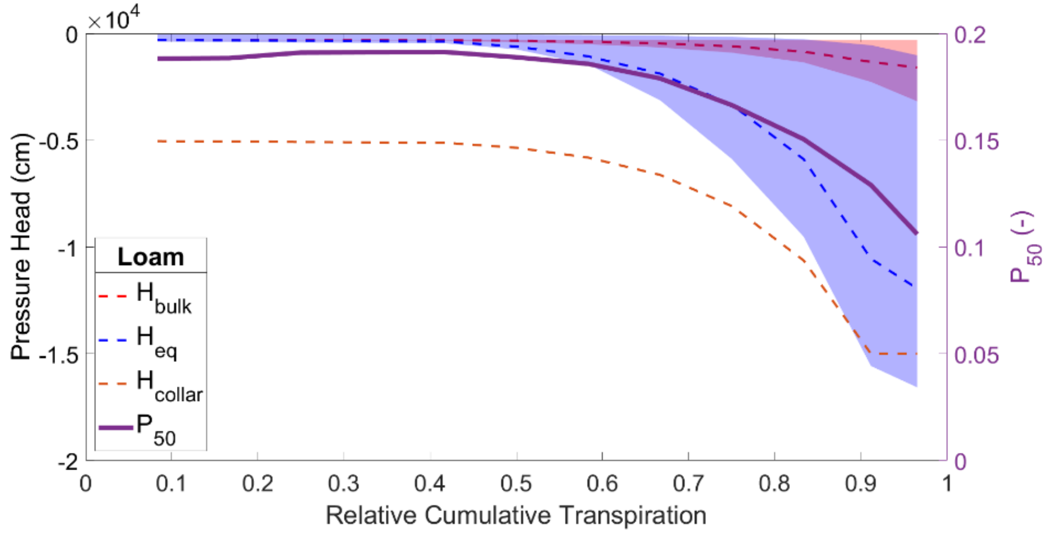
Drying soil with rhizosphere K drop

ARF reaches values below 10 in certain soils



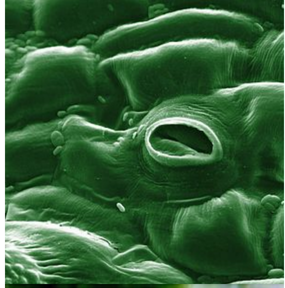


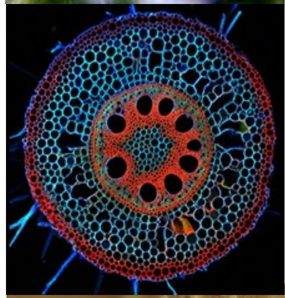




Conclusions

- Catenary hypothesis allows representing real root systems
- A series of modeling tools exist to estimate plant conductances
  - Effective parameters exist, that represent the complex 3D root system hydraulic architecture (Krs, SSF, Couvreur et al., 2012)
  - Effective parameters can be linked to root traits with the need of a root system map (Meunier et al.,2017, 2019)
- (root hydraulic traits can be measured or deducted from anatomical measurements)
- The distribution of uptake plays a key role on the soil resistance: architectural models show ARF below 10% when variability in soil and root properties is accounted for

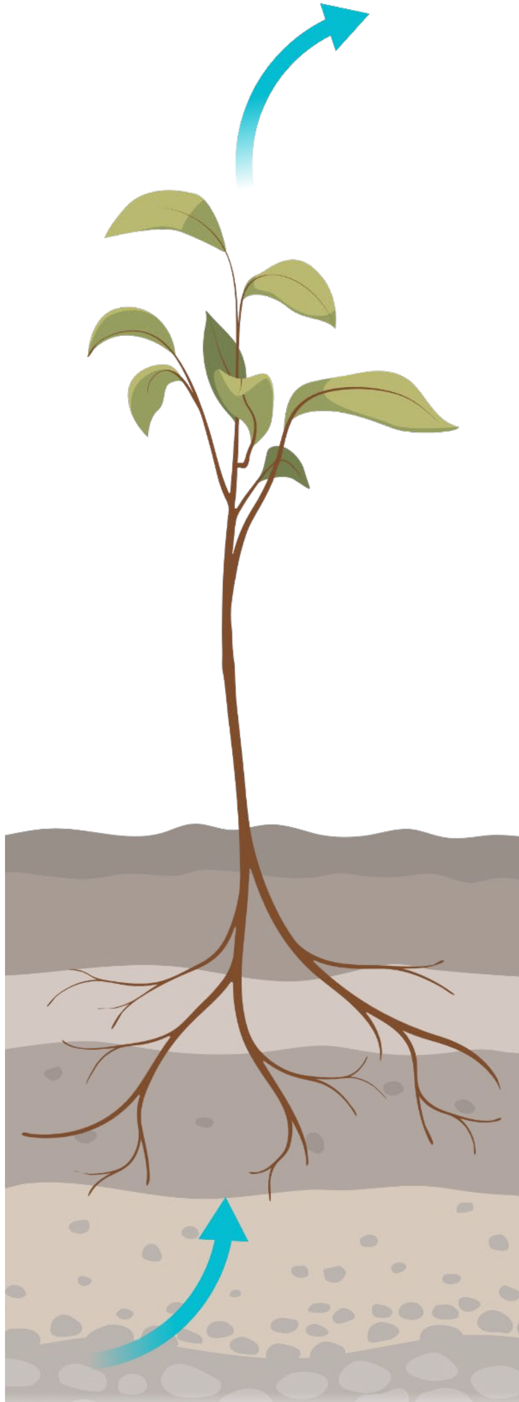





UCLouvain JÜLICH FORSCHUNGSZENTRUM

Thank you

- R-SWMS: https://sites.uclouvain.be/RSWMS/
- MARSHAL: https://marshal-root.github.io/
- Lab: https://javaux.wixsite.com/soilroothydraulics



Open questions

- xxx

A simplified soil-plant hydraulic model

Xylem

$$T = -K_x(\psi)(d\psi + dz) \qquad k_x = k_{max}\left(\frac{\psi}{\psi_{0x}}\right)^{\tau x}$$

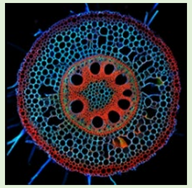
$\psi_{\text{xyl,leaf}}$

Xylem conductance: number and radius vessels, cavitation

$\psi_{\text{xyl,root}}$

Roots: Couvreur model (2012)

$$T = -K_{root}\,d\psi$$



Root conductance: root architecture, anatomy, AQP

$\psi_{\text{soil,root}}$

$K_{plant} = (1/K_{root} + 1/K_x)^{-1}$

Soil: Gardner model (Schroeder et al., 2008)

$$\frac{T}{2\pi r L} = -k_{soil}(\psi)\frac{\partial\psi}{\partial r} \qquad k_{soil} = k_{sat}\left(\frac{\psi}{\psi_0}\right)^{\tau}$$

Rhizosphere conductance: soil, root hairs, mucilage, mycorrhiza, root architecture

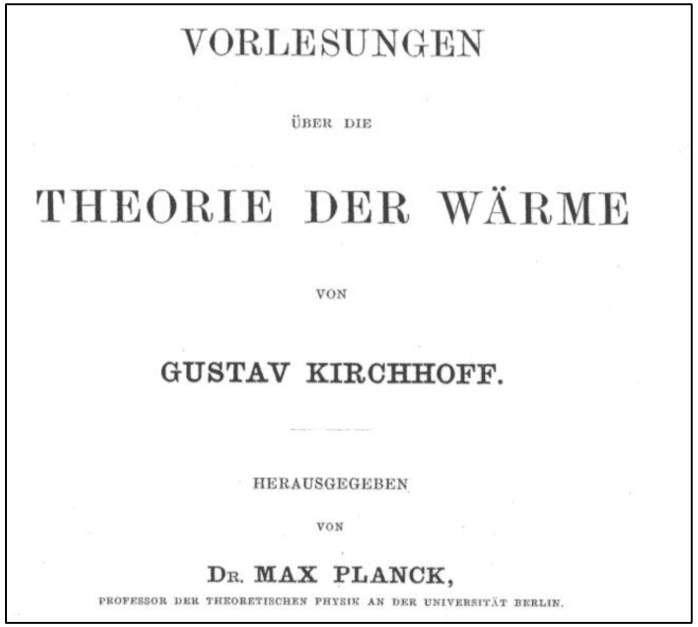
ψ_{soil}

Solving the non-linearities: The Kirchhoff transformation

We define the matric flux potential:

$$\phi(\psi) = \int_{-\infty}^{\psi} k(x)\,dx$$

$$q = -k(\psi)\frac{\partial \psi}{\partial r} = -\frac{\partial \phi}{\partial r}$$


VORLESUNGEN

ÜBER DIE

THEORIE DER WÄRME

VON

GUSTAV KIRCHHOFF.

HERAUSGEGEBEN

VON

DR. MAX PLANCK,

PROFESSOR DER THEORETISCHEN PHYSIK AN DER UNIVERSITÄT BERLIN.

$$\phi_{soil,root} = -\frac{T}{2\pi r L}\left(\frac{r_0}{2} - r_0 r_2^2 \frac{\ln(r_2/r_0)}{r_2^2 - r_0^2}\right) + \left(\phi_{soil,bulk}\right)$$

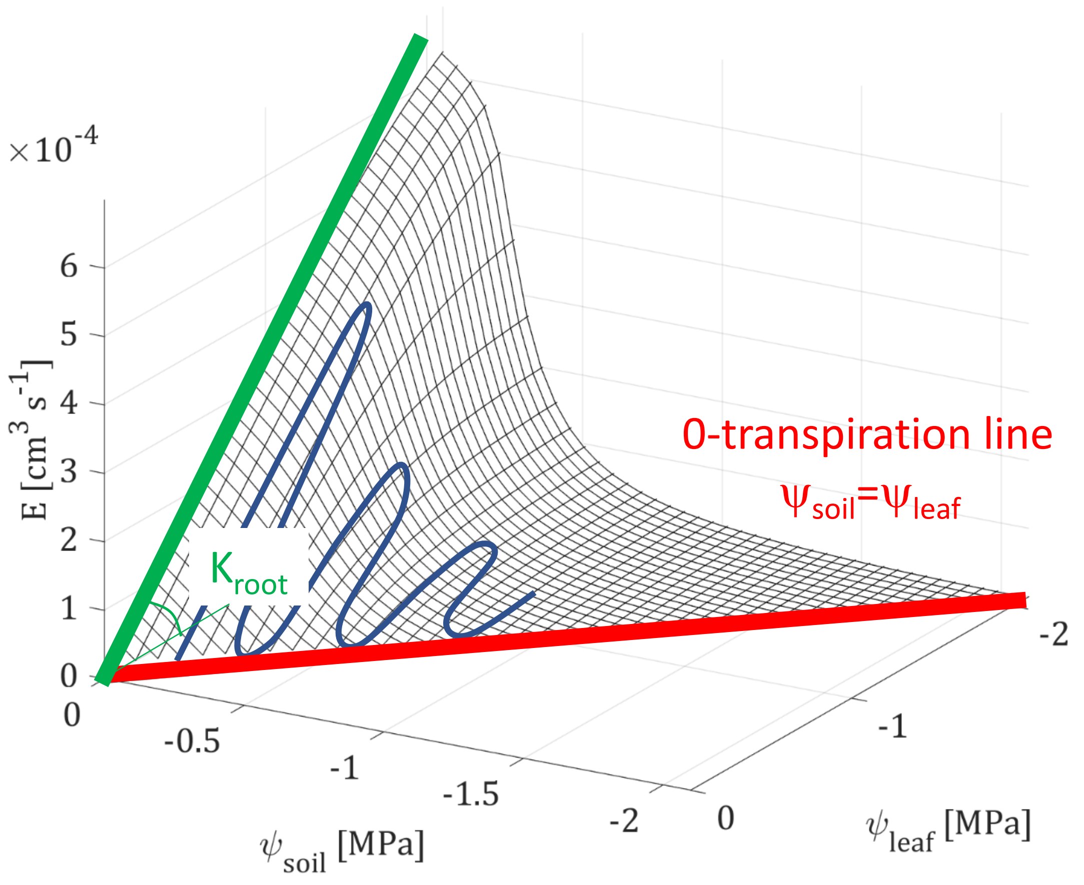
$$\phi_{xyl,root} = -T + \left(\phi_{soil,root}\right)$$

$$\phi_{xyl,leaf} = -T + \left(\phi_{xyl,root}\right)$$

Here without gravity – but it can be included

Plant hydraulic status

- 3-D surface of possible plant hydraulic status
- Function of plant (root/xylem) and soil hydraulics
- No stomatal control (yet)



Surface validation

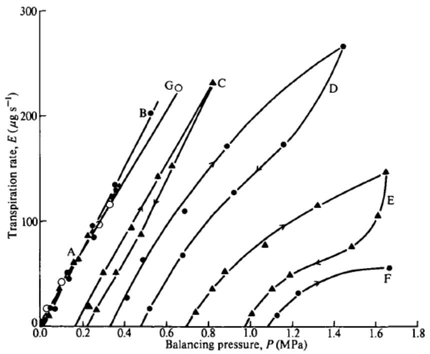
Fitting soil and root hydraulics properties to Passioura data (1980)

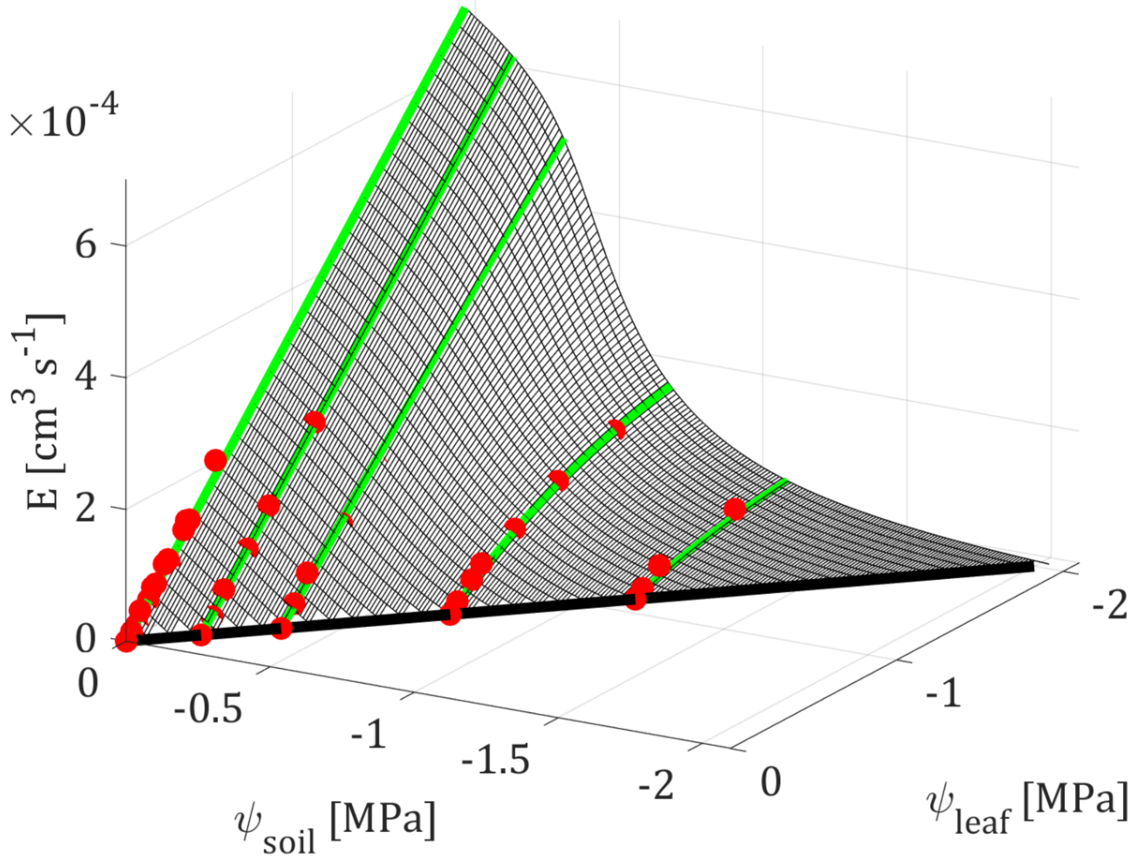
(no xylem limitation)

Journal of Experimental Botany, Vol. 31, No. 120, pp. 333–345, February 1980

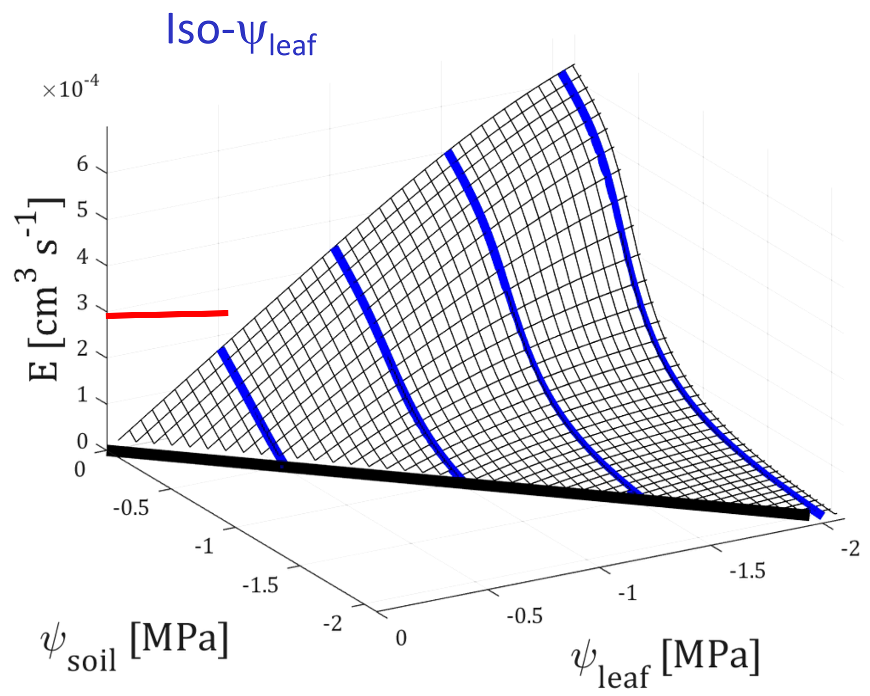
The Transport of Water from Soil to Shoot in Wheat Seedlings

J. B. PASSIOURA





Physical constraints on water flow



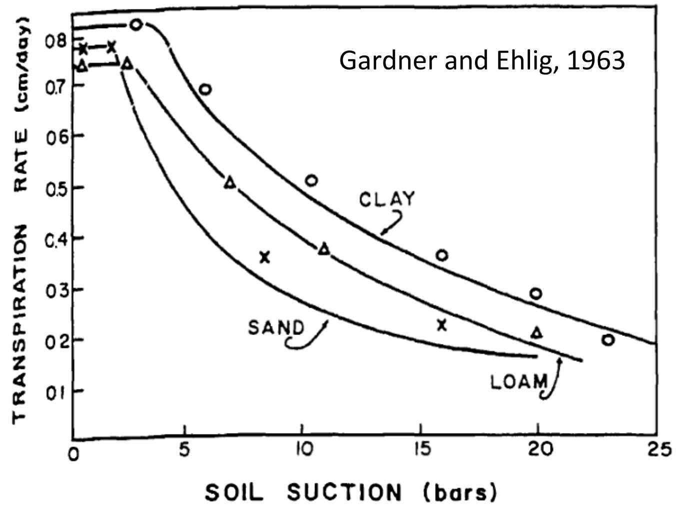


Fig. 4. Average daily transpiration rate for birdsfoot trefoil in shallow containers as a function of soil suction. The symbols represent experimental values obtained from Figure 2. The smooth curves were calculated theoretically. The soils are the same as for Figure 2.

Stress functions are plant- and soil-dependent

Questions

- Transpiration vs. Ψ_{soil} /vs. Ψ_{leaf} : two sides of the same coin?
- How do hydraulic limitations impact transpiration?
- Can we come up with a simple model for stomata control?

Stomatal regulation

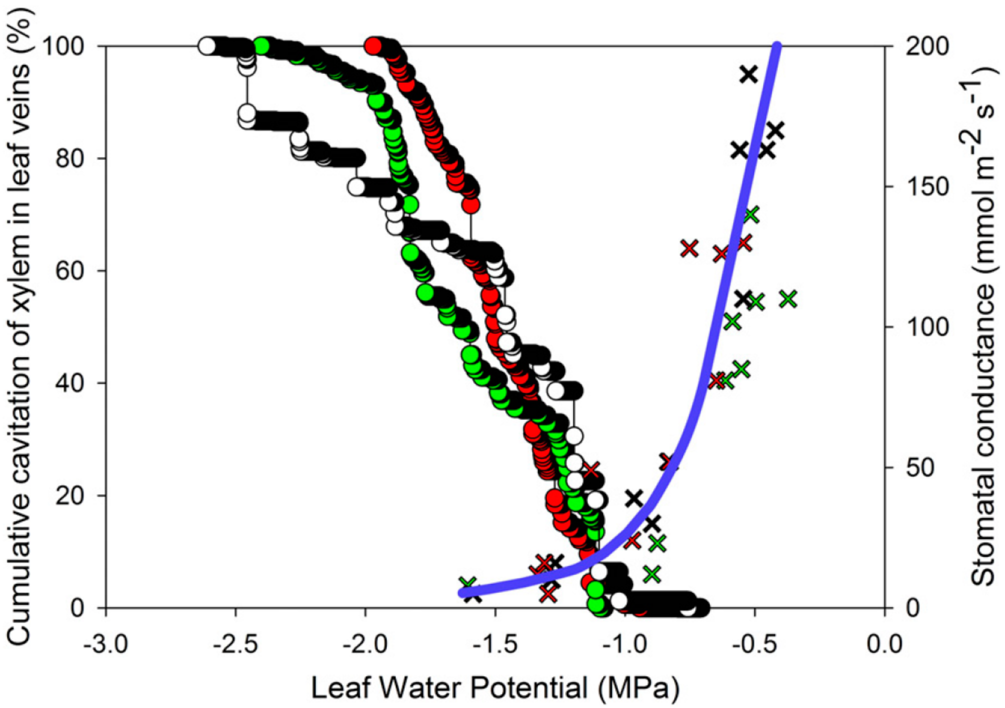
Update on Stomatal Evolution

Evolution of the Stomatal Regulation of Plant Water Content[OPEN]

Timothy J. Brodribb* and Scott A. M. McAdam
School of Biological Sciences, University of Tasmania, Hobart TAS 7001, Australia
ORCID IDs: 0000-0002-4964-6107 (T.J.B.); 0000-0002-9625-6750 (S.A.M.M.).

Hyp 1: Stomatal regulation is needed to avoid cavitation

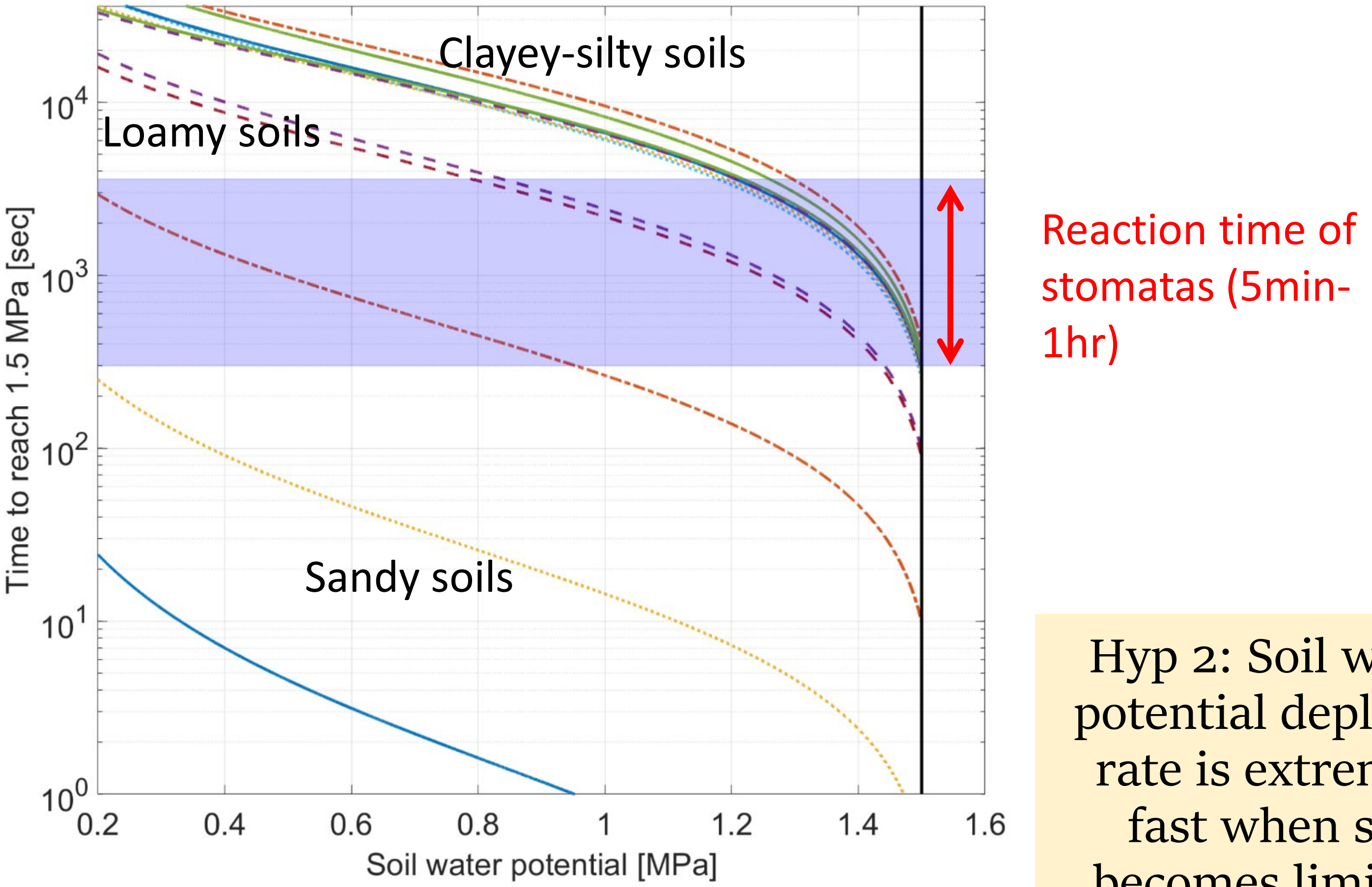
Figure 2. Stomata in the earliest vascular plants probably first closed to prevent cavitation of the vascular system, a function that appears to remain conserved until the present. Data here show the trajectory of stomatal closure (blue line) with respect to leaf water potential as three tomato plants were subjected to gradual soil drying (green, red, and black crosses). Close to the water potential of complete stomatal closure, the process of xylem cavitation begins (three traces for leaves from three individuals are shown; black, red, and green circles). Cavitation curves show the accumulation of cavitation events in the leaf veins of three tomato plants as they desiccate (data from Skelton et al. (2017)).



Brodribb and McAdam, 2017

Soil water depletion rate

$$\tau(\psi) = \int_{\psi_s}^{1.5} \frac{1}{\partial\psi/\partial t} d\psi = \int_{\psi_s}^{1.5} \frac{C(\psi)}{\partial\theta/\partial t} d\psi$$

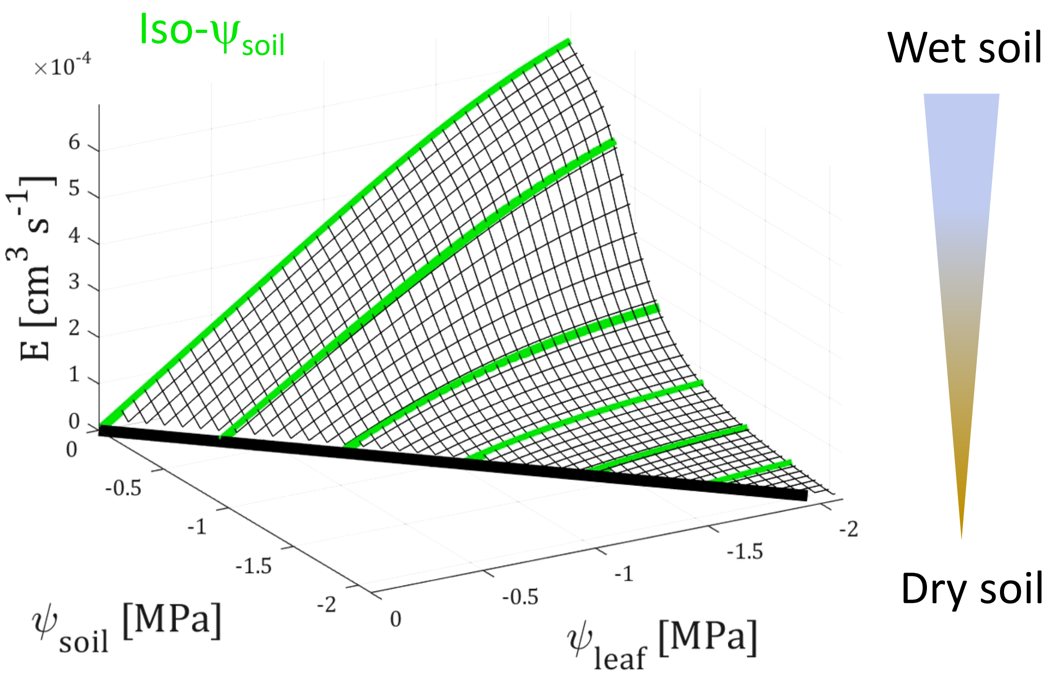


For a steady water depletion rate of 0.1 cm³/cm³/d

Hyp 2: Soil water potential depletion rate is extremely fast when soil becomes limiting

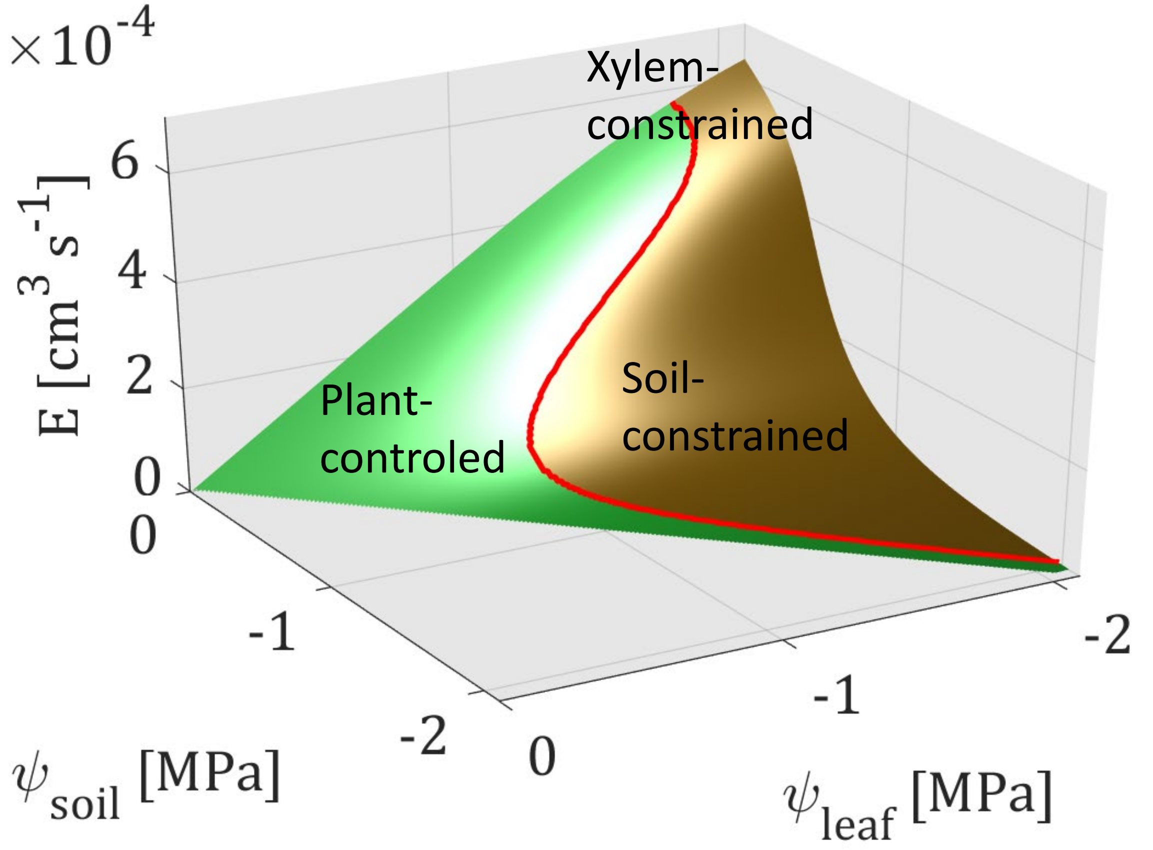
UCLouvain JÜLICH FORSCHUNGSZENTRUM

Physical constraints on water flow



Without stomatal control, when the soil is dry, $dE/d\psi_{leaf}$ decreases fast

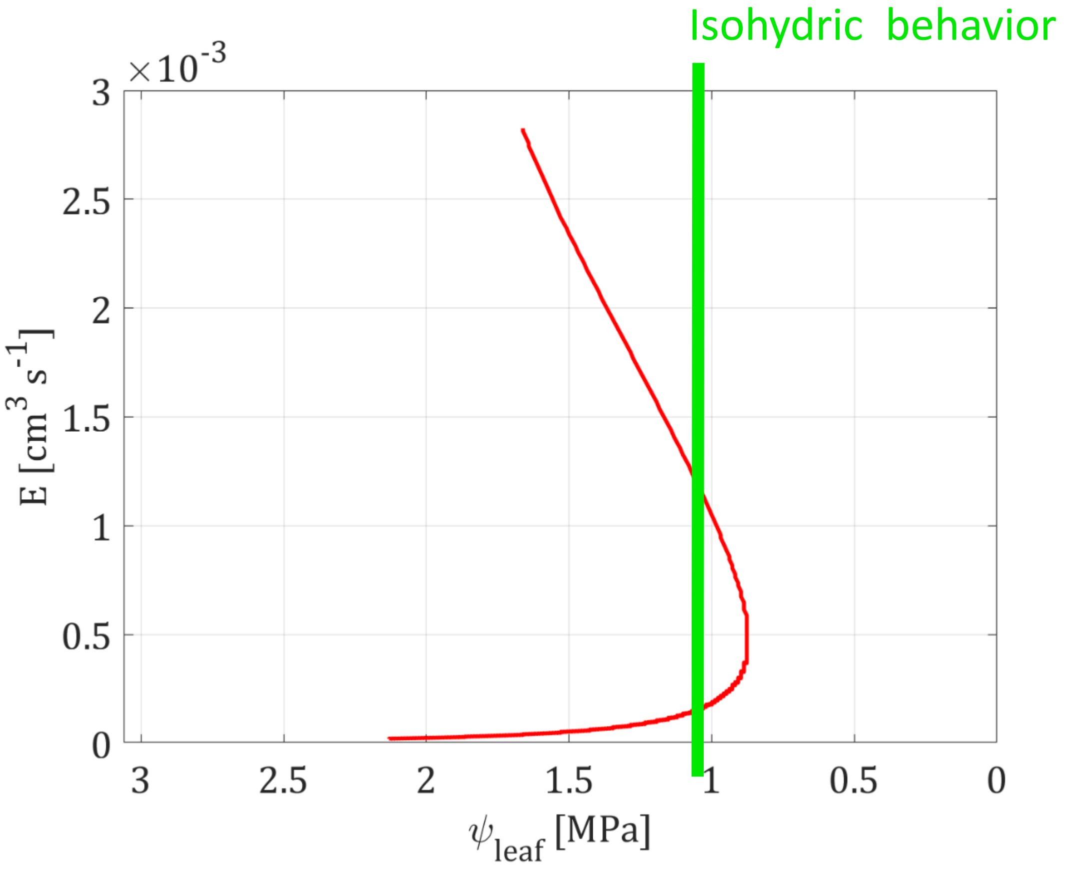
Physical constraints on water flow

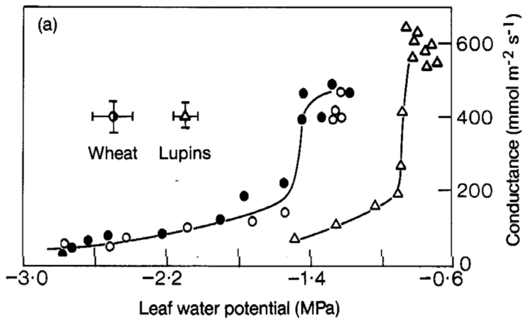


Beyond the **red line**, the water flow becomes not linear (=not *convenient*).

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Physical constraints and biological control on water flow





Henson et al., 1989

Experimental evidence

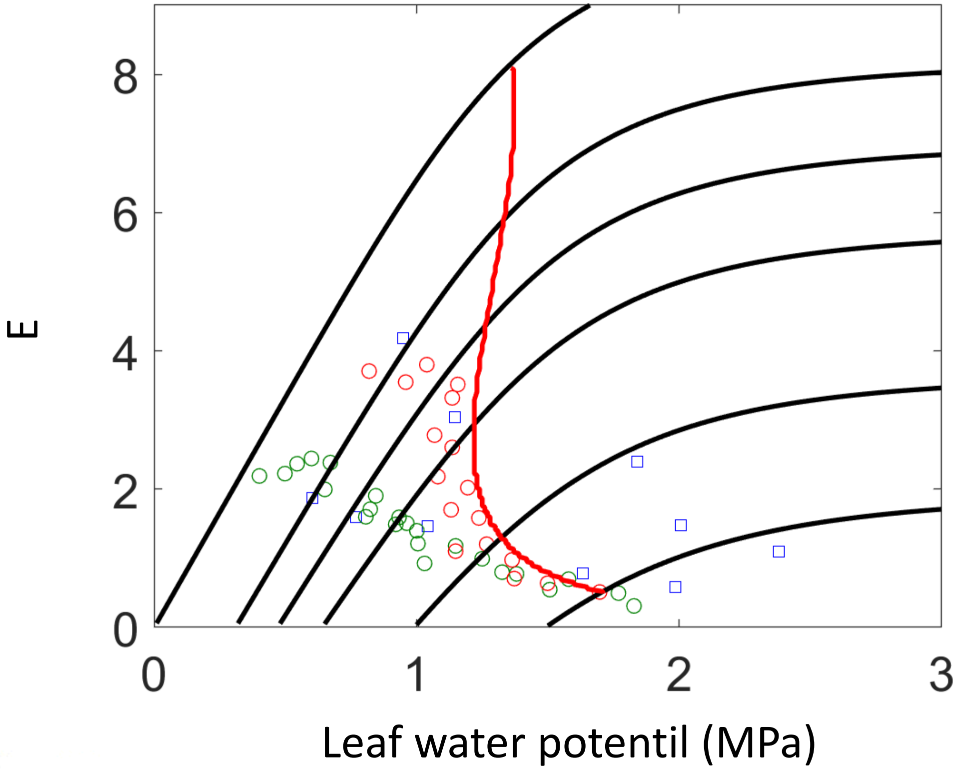
The responses of stomata and leaf gas exchange to vapour pressure deficits and soil water content

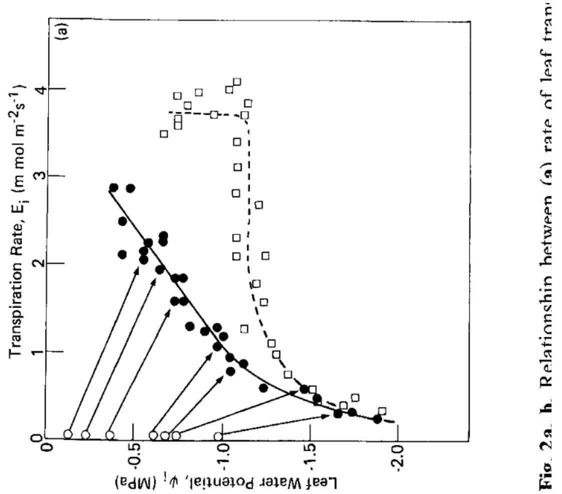
III. In the sclerophyllous woody species *Nerium oleander*

T. Gollan[1], N.C. Turner[1,2], and E.-D. Schulze[1]

[1] Lehrstuhl für Pflanzenökologie, Universität Bayreuth, Postfach 3008, D-8580 Bayreuth, Federal Republic of Germany

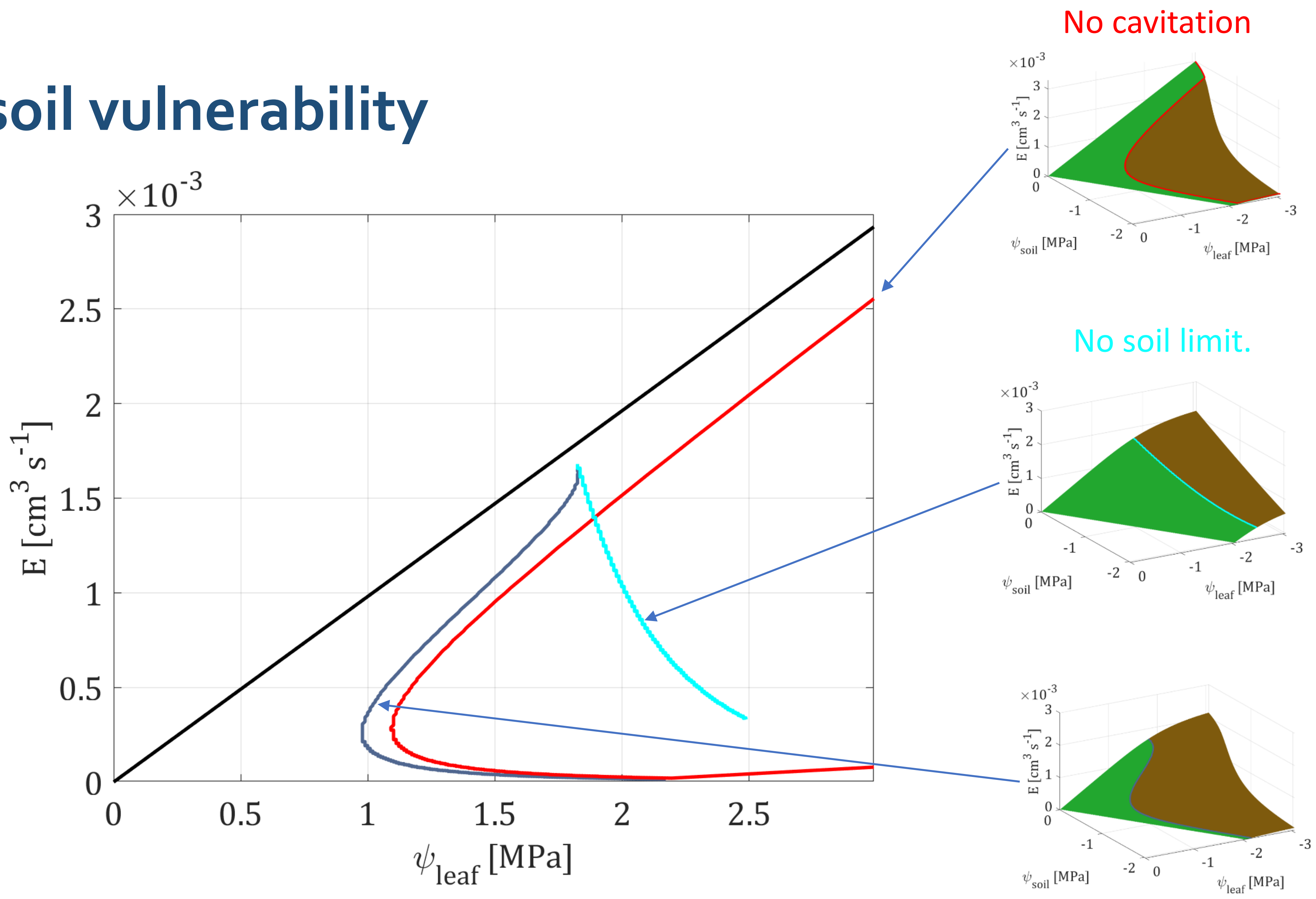
[2] CSIRO Dryland Crops and Soils Research Program, Private Bag, P.O., Wembley, W.A. 6014, Australia



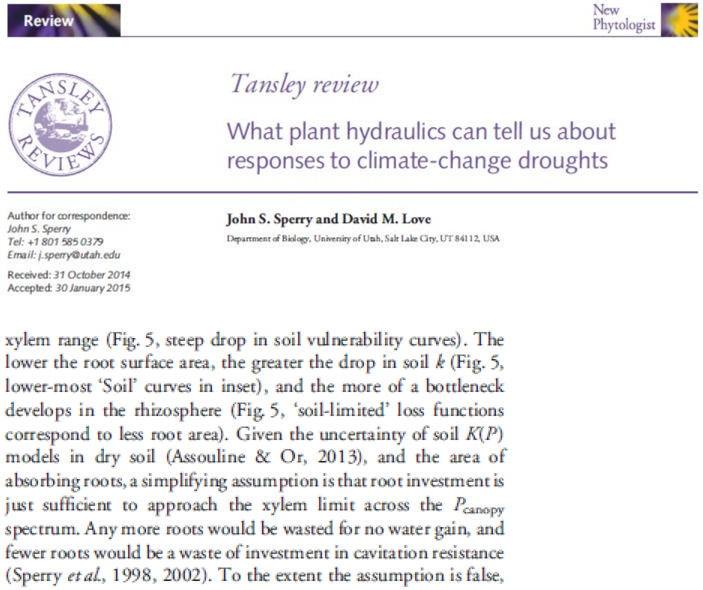


Gollan et al., 1985

Xylem or soil vulnerability



Similarity to Sperry & Love concept



Review

New Phytologist

Tansley review

What plant hydraulics can tell us about responses to climate-change droughts

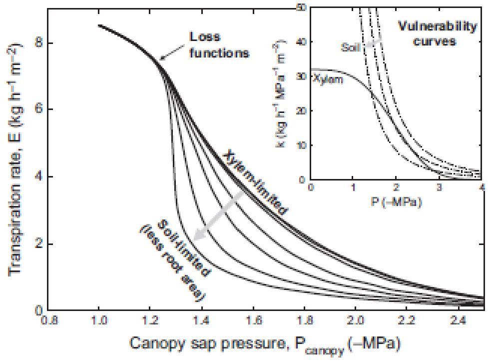
Author for correspondence:
John S. Sperry
Tel: +1 801 585 0379
Email: j.sperry@utah.edu

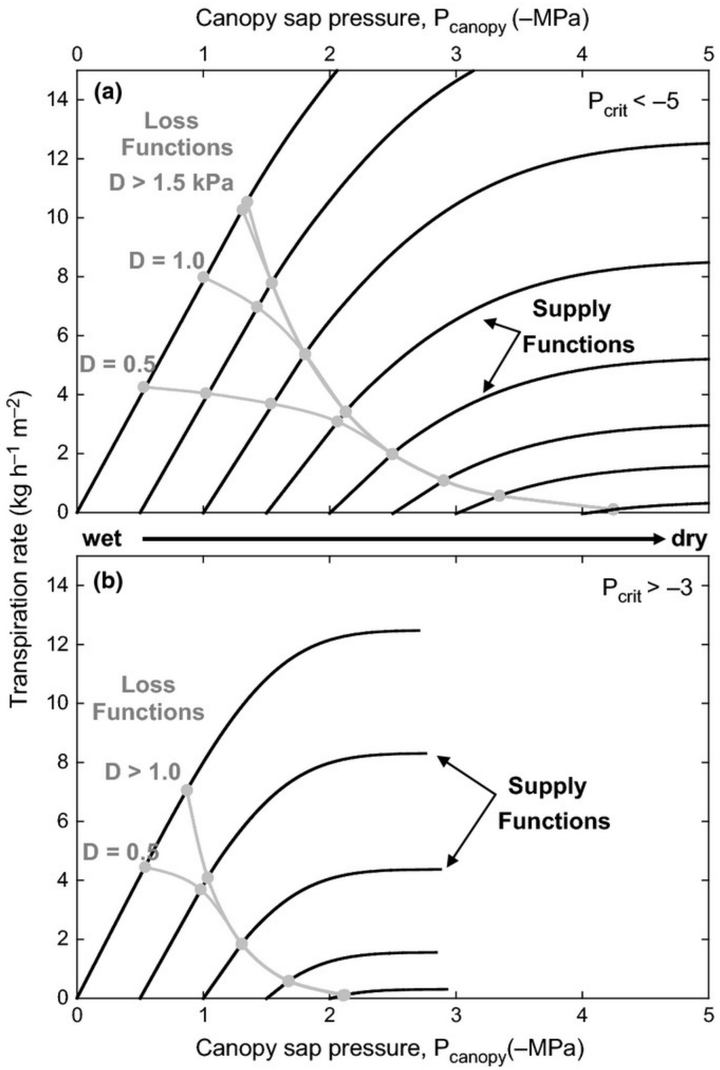
John S. Sperry and David M. Love

Department of Biology, University of Utah, Salt Lake City, UT 84112, USA

Received: 31 October 2014
Accepted: 30 January 2015

xylem range (Fig. 5, steep drop in soil vulnerability curves). The lower the root surface area, the greater the drop in soil *k* (Fig. 5, lower-most 'Soil' curves in inset), and the more of a bottleneck develops in the rhizosphere (Fig. 5, 'soil-limited' loss functions correspond to less root area). Given the uncertainty of soil *K*(*P*) models in dry soil (Assouline & Or, 2013), and the area of absorbing roots, a simplifying assumption is that root investment is just sufficient to approach the xylem limit across the P_{canopy} spectrum. Any more roots would be wasted for no water gain, and fewer roots would be a waste of investment in cavitation resistance (Sperry *et al.*, 1998, 2002). To the extent the assumption is false,





UCLouvain JÜLICH FORSCHUNGSZENTRUM

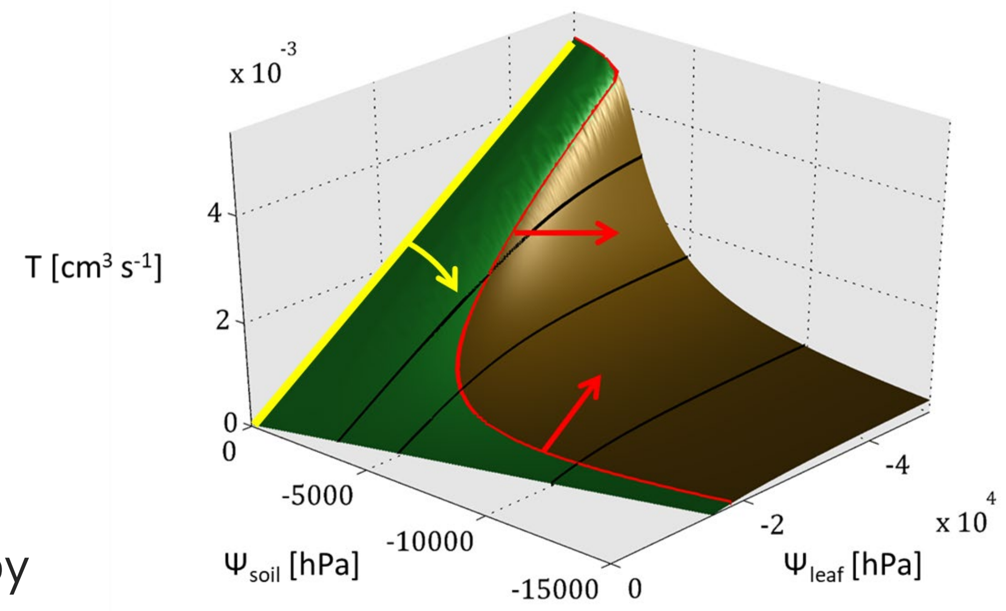
Sperry and Love, 2015

Additions to Sperry's concept

- Soil is the main factor inducing non-linearities in the relationship between E & ψ_{leaf}

- Plants stomata close to prevent cavitation due to a quick decrease of ψ_{soil}

- Plants can respond to it not only by closing stomata – they can change the surface.



Plant strategies

Received 18 Jul 2014 | Accepted 24 Sep 2014 | Published 5 Nov 2014 DOI: 10.1038/ncomms6365 OPEN

Circadian rhythms of hydraulic conductance and growth are enhanced by drought and improve plant performance

Cecilio F. Caldeira[1], Linda Jeanguenin[2], François Chaumont[2] & François Tardieu[1]

, Vol. 61, No. 5, pp. 1431–1440, 2010
nce Access publication 8 February, 2010
ccess charges (see http://jxb.oxfordjournals.org/open_access.html for further details)

Journal of Experimental Botany
www.jxb.oxfordjournals.org

RESEARCH PAPER

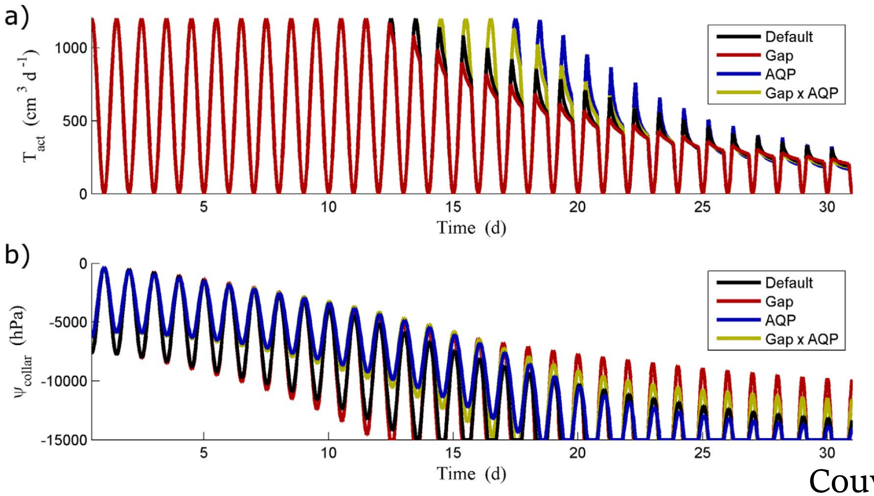
Terminal drought-tolerant pearl millet [*Pennisetum glaucum* (L.) R. Br.] have high leaf ABA and limit transpiration at high vapour pressure deficit

Jana Kholová[1,2], C. T. Hash[1], P. Lava Kumar[3], Rattan S. Yadav[4], Marie Kočová[2] and Vincent Vadez[1,*]

New Phytologist

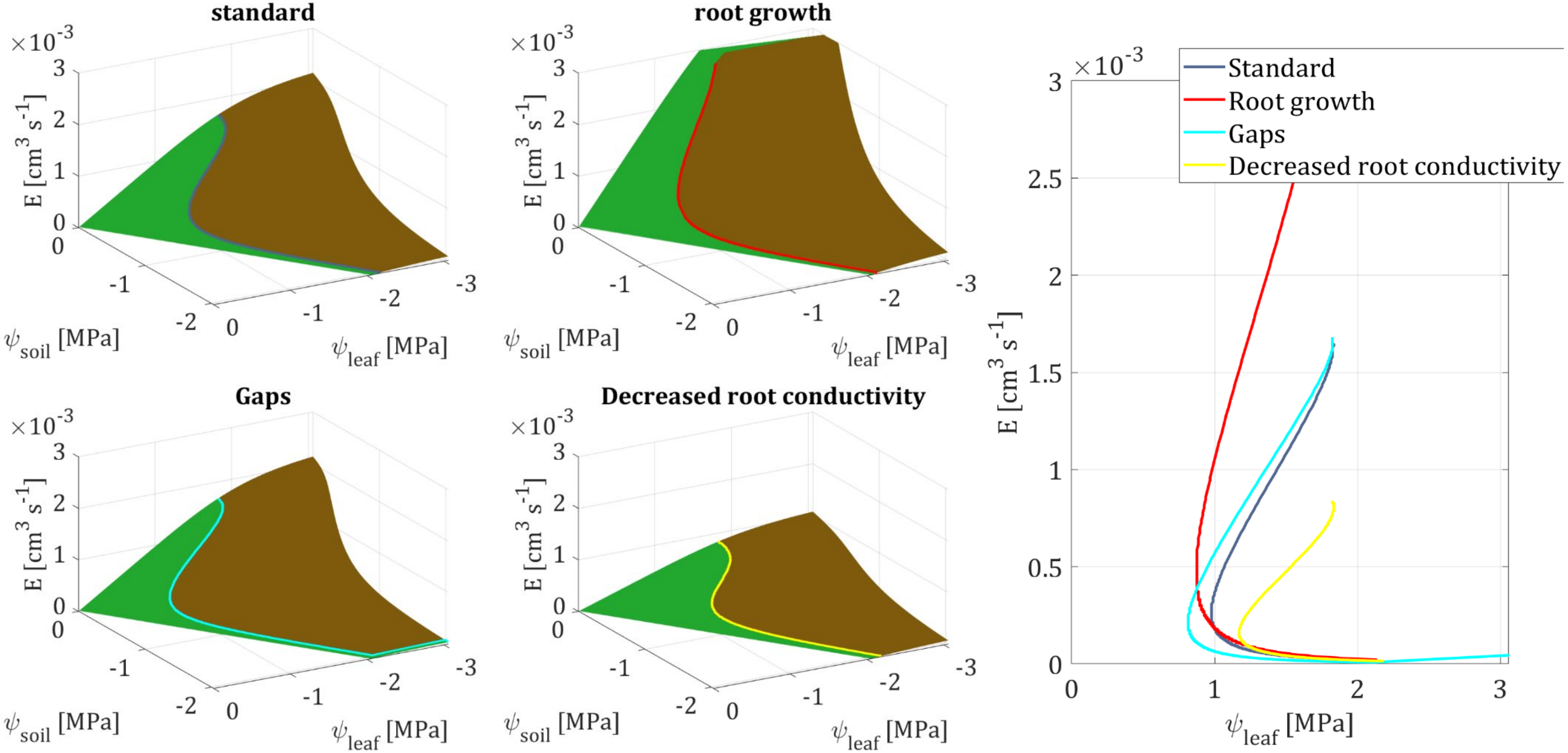
Root hairs enable high transpiration rates in drying soils

Andrea Carminati[1], John B. Passioura[2], Mohsen Zarebanadkouki[1], Mutez A. Ahmed[1,3,4], Peter R. Ryan[2], Michelle Watt[5] and Emmanuel Delhaize[2]



Couvreur et al., 2014

Plant strategies

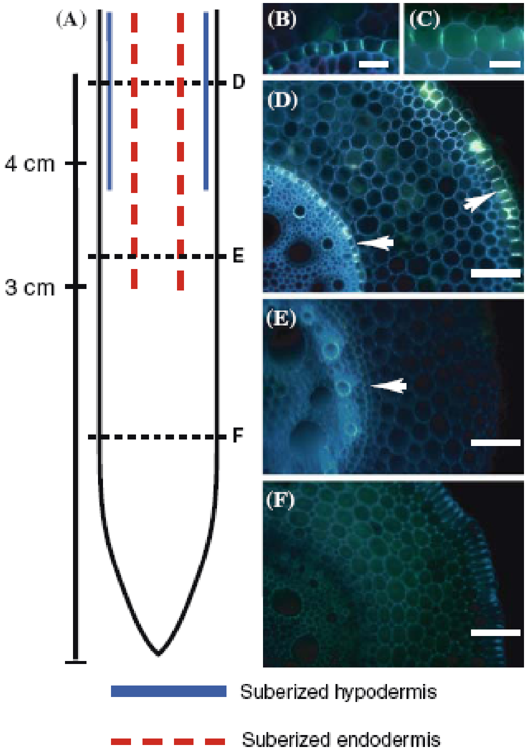


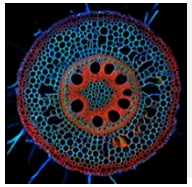
UCLouvain JÜLICH FORSCHUNGSZENTRUM

Water flow resistances in the SPAC

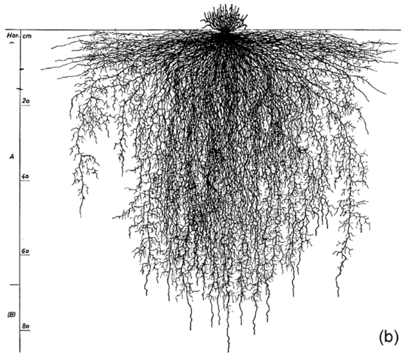
Impacts on water flu

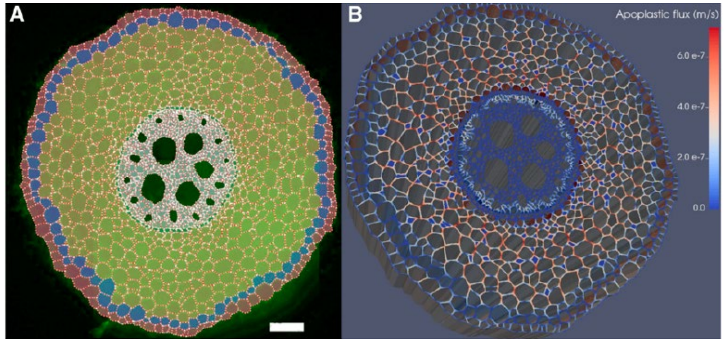
- Xylem vessel diam
- Suberization
- Aquaporin activity
- Root growth/matu
- Root radial conduc
- Root hairs
- …





Root conductance: root architecture, anatomy, AQP





Couvreur et al., 2018

Water flow resistances in the SPAC

Xylem conductance: number and radius vessels, cavitation

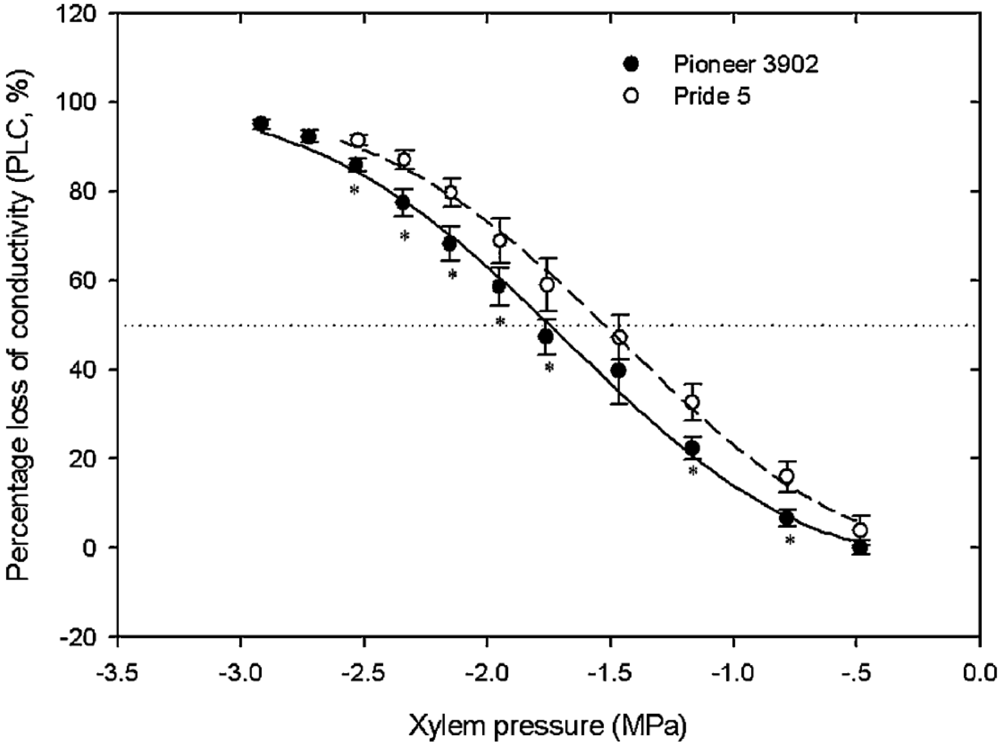
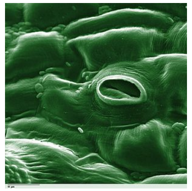
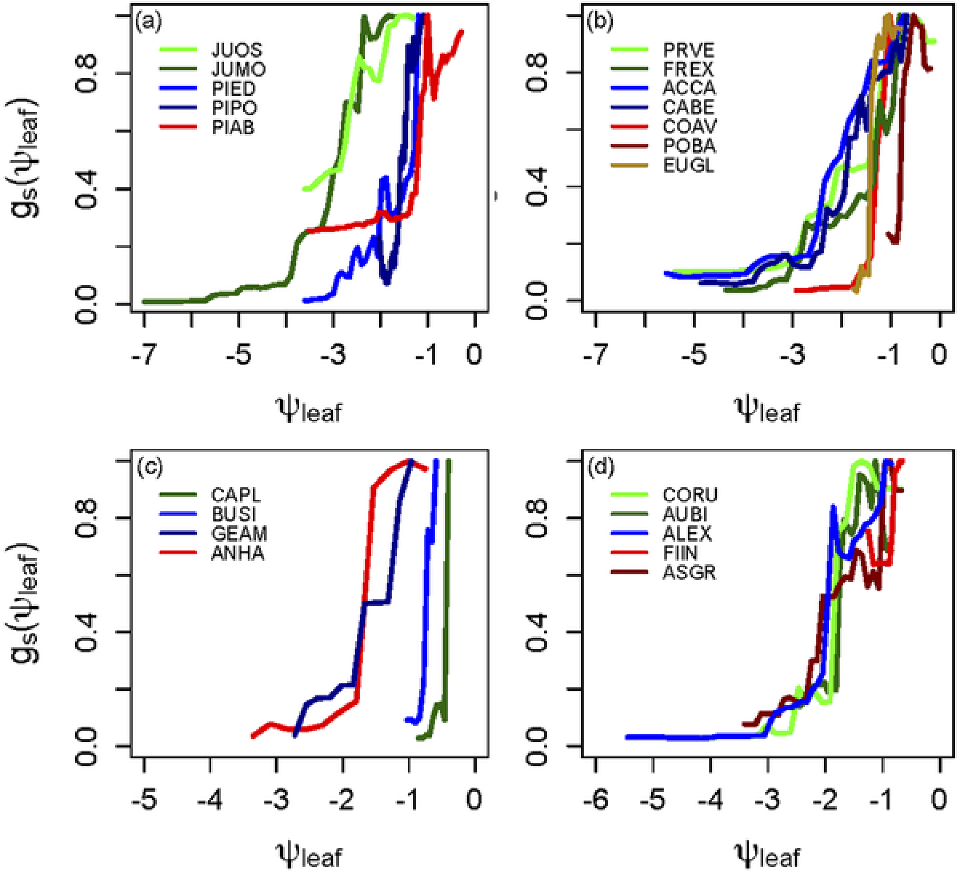


Fig. 2. Xylem vulnerability curves of the stems of two corn hybrids. Percentage loss of conductivity (PLC) is calculated based on individual estimated K_{max} by Weibull function. The reference line corresponds to 50% PLC. Significant symbols, lines, and error bars are same as in Fig. 1.

Li et al., 2009

Water flow resistances in the SPAC





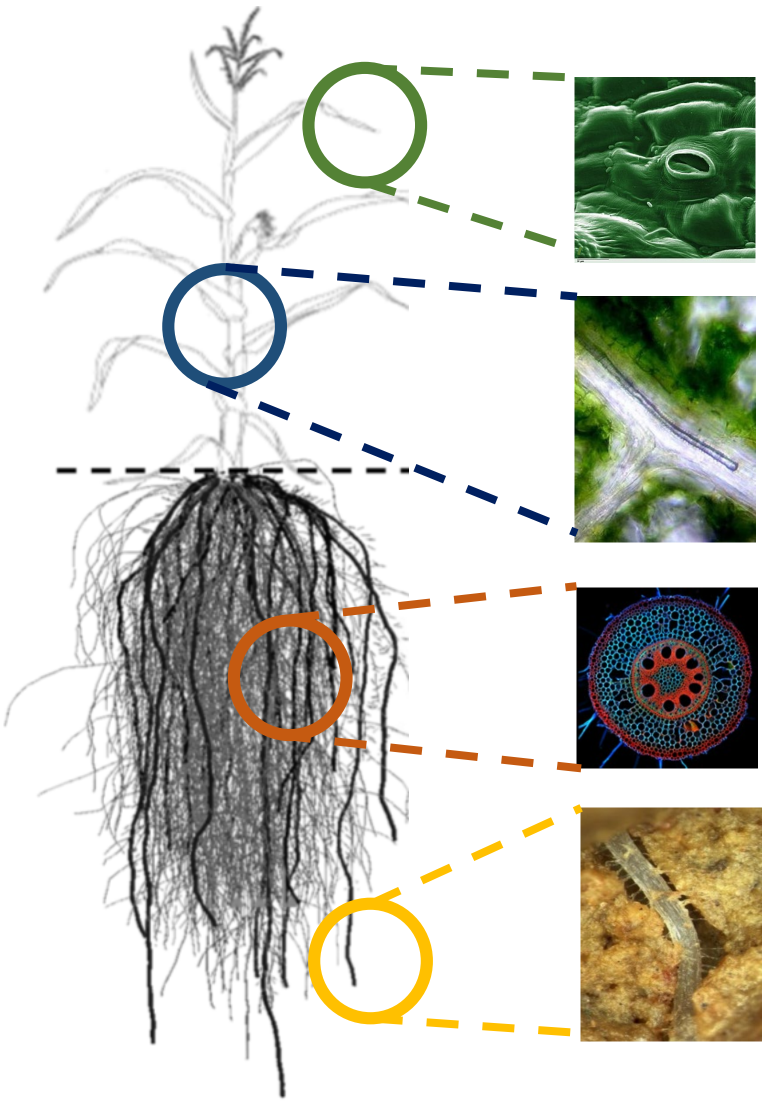
Stomatal conductance:
Regulates transpiration, depends on ABA, ψ_x

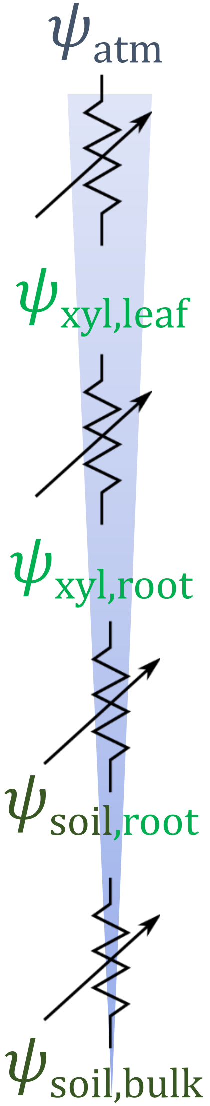
There is a relation between leaf water potential and stomata conductance

Fig 1. Partial dependency of stomatal conductance (gs) on measured leaf water potential (ψleaf, in MPa) in (a) temperate gymnosperm species, (b) temperate angiosperm species, (c) tropical deciduous species, and (d) tropical evergreen species.

Anderegg et al., 2017

Water flow resistances in the SPAC





Stomatal conductance: Regulates transpiration, depends on ABA, ψ_x

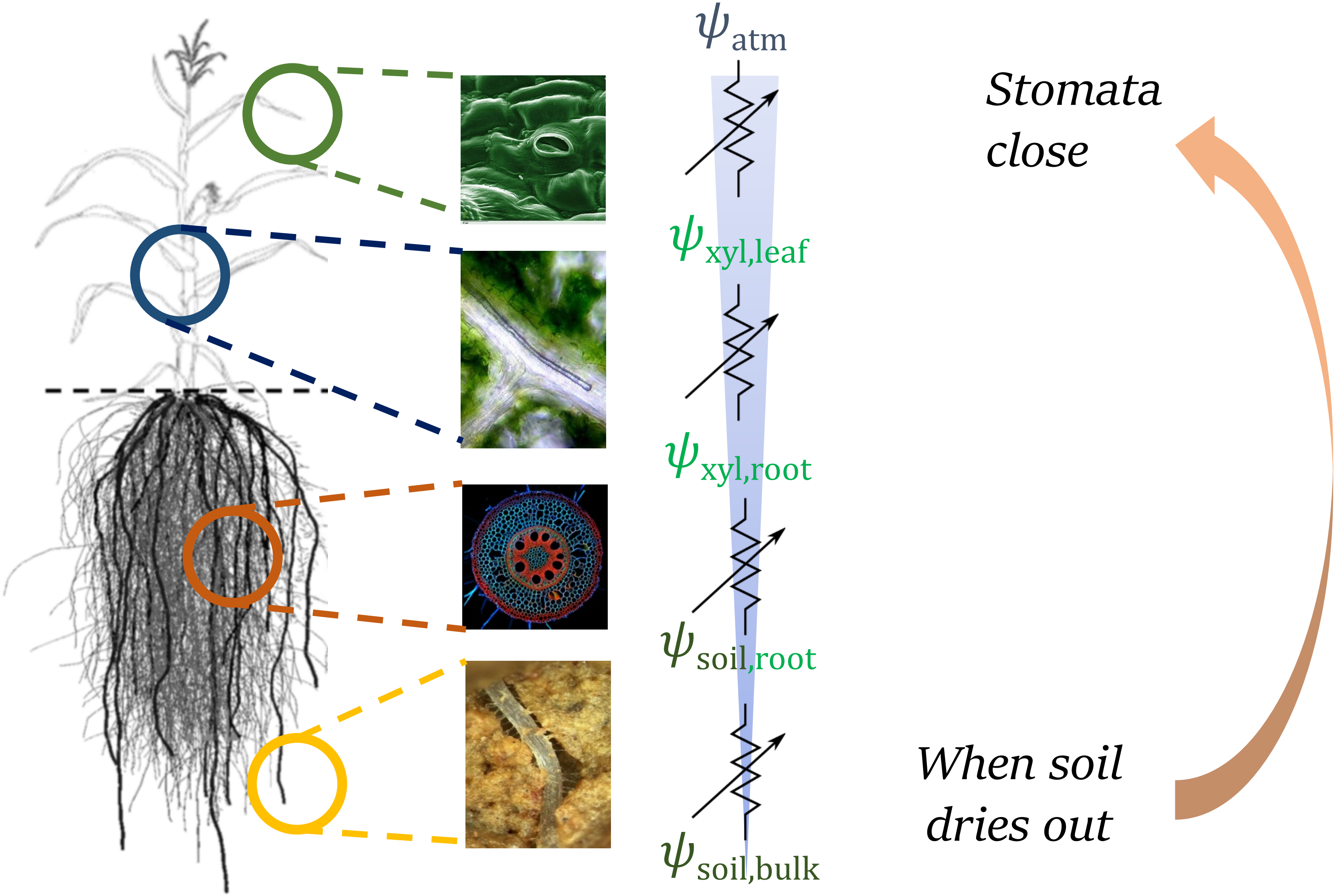
Xylem conductance: number and radius vessels, cavitation

Root conductance: root architecture, anatomy, hydropatterning, AQP

Rhizosphere conductance: soil, root hairs, mucilage, mycorrhiza, root architecture

UCLouvain JÜLICH FORSCHUNGSZENTRUM

Water flow resistances in the SPAC



Stomata close

When soil dries out

Impact of water deficit on transpiration

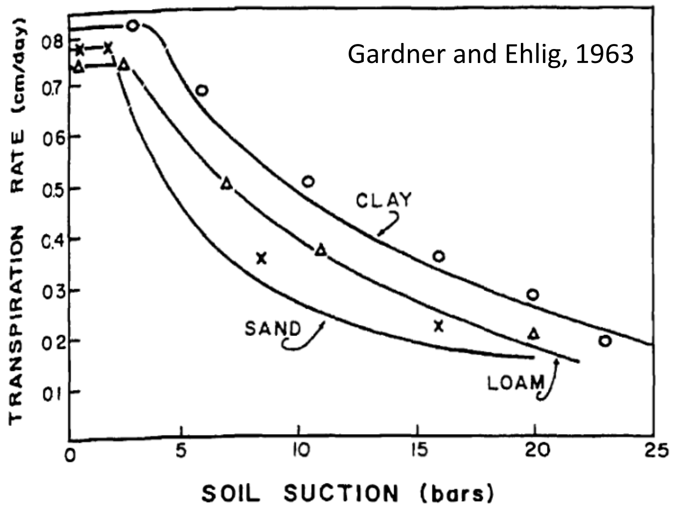


Fig. 4. Average daily transpiration rate for birdsfoot trefoil in shallow containers as a function of soil suction. The symbols represent experimental values obtained from Figure 2. The smooth curves were calculated theoretically. The soils are the same as for Figure 2.

There is a relation between soil water potential and stomatal conductance

(function of Tpot)

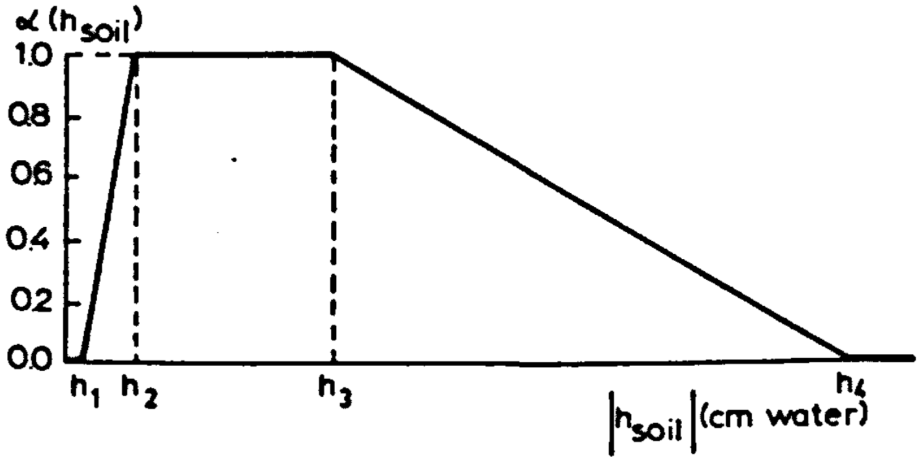


Figure 59. General shape of the dimensionless sink term variable, $\alpha(h)$, as a function of the absolute soil water pressure head, h (Feddes et al., 1978).

UCLouvain JÜLICH FORSCHUNGSZENTRUM