# A trait-based plant hydraulics scheme for water stress in CLM(ED)


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Los Alamos NATIONAL LABORATORY EST. 1943
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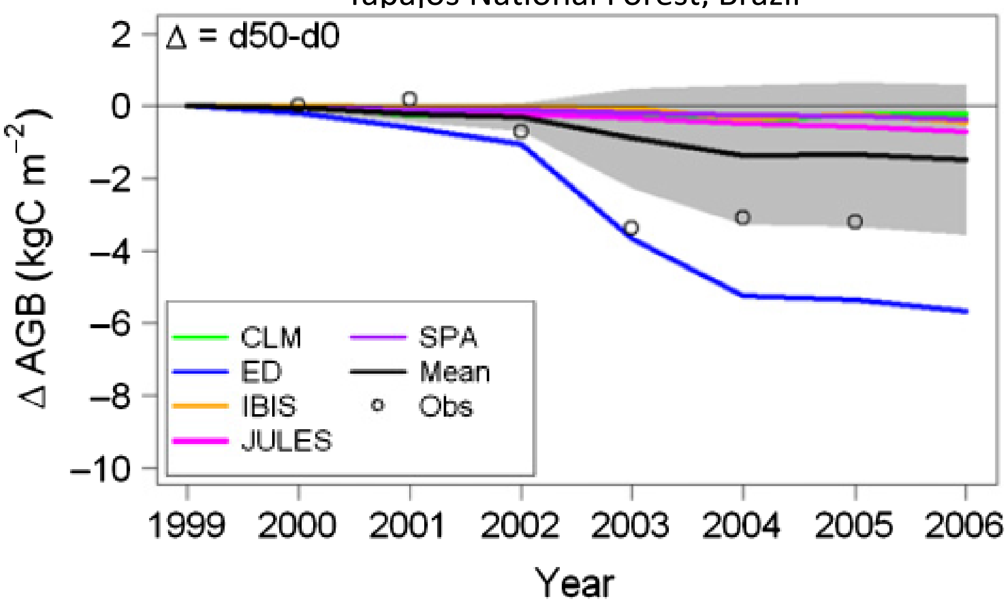
UNIVERSITY OF LEEDS

# Motivation for the Trait-Based, Size-Structured Approach

- **Why plant hydraulics?**
  - *BTRAN primarily informed by soils*
  - *Poorly captures drought experiment data*

Drought effect on biomass, Obs and Simulated
Tapajos National Forest, Brazil

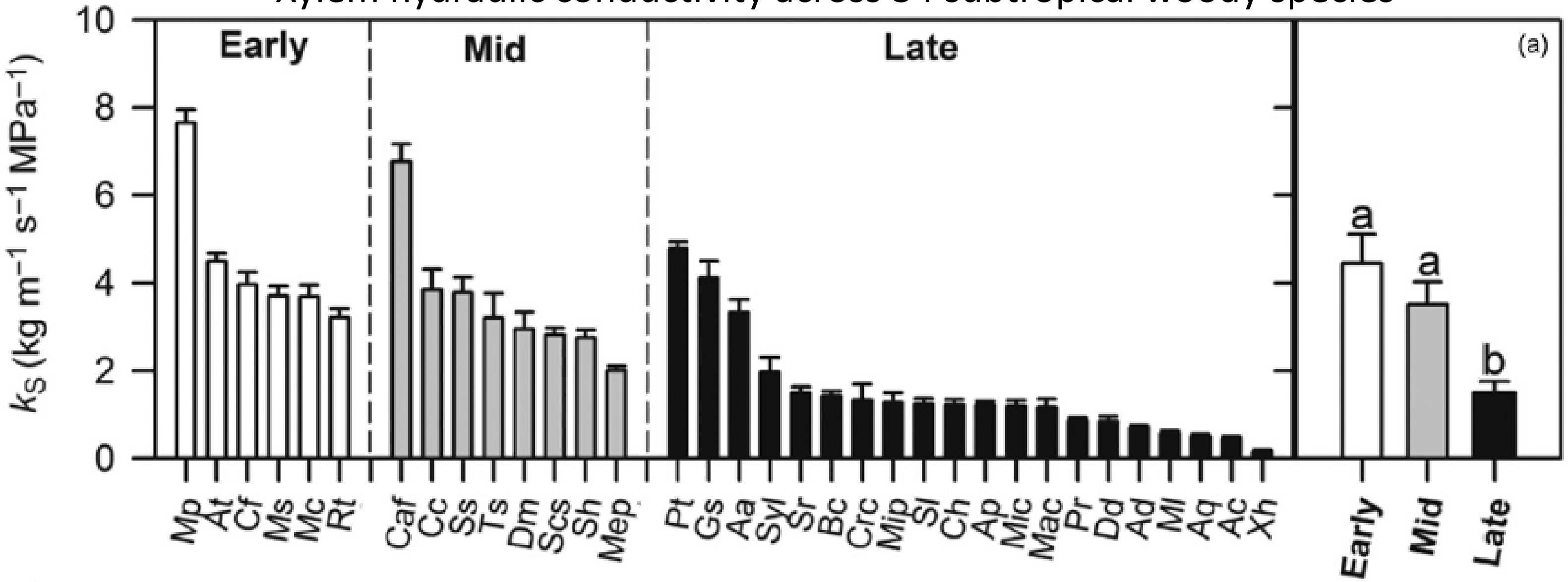



Powell et al. 2013 *New Phyt*

# Motivation for the Trait-Based, Size-Structured Approach

- **Why traits?**
  - *Large differences among individuals, even within the same PFT*

Xylem hydraulic conductivity across 34 subtropical woody species

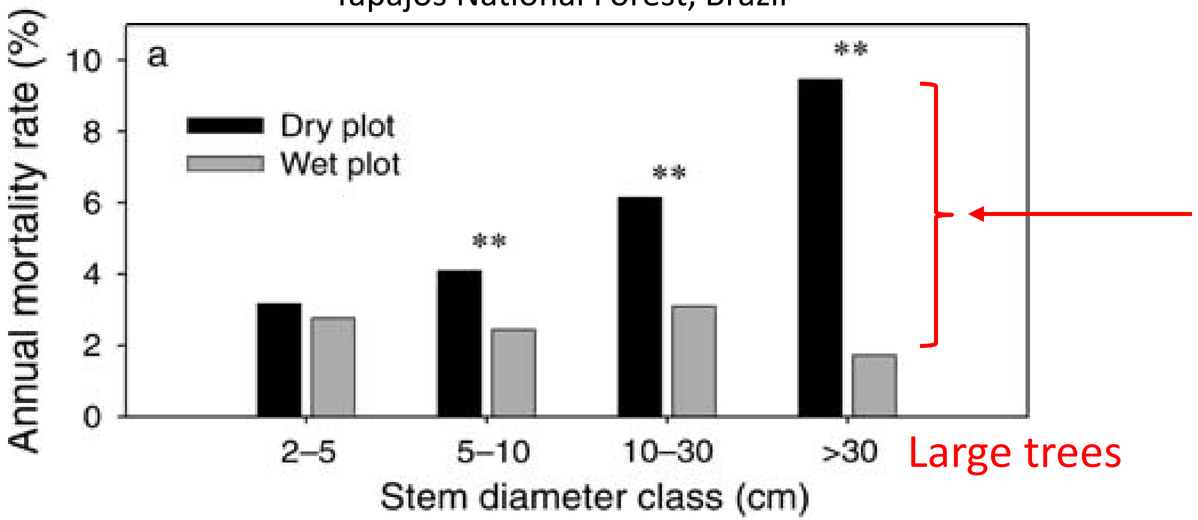



Zhu et al. 2013 *PCE*

# Motivation for the Trait-Based, Size-Structured Approach

- **Why CLM(ED)?**
  - *Size-structured (potential for height effects on mortality)*
  - *Prevents all-or-nothing mortality response*

Drought effect on mortality, by tree size
Tapajos National Forest, Brazil

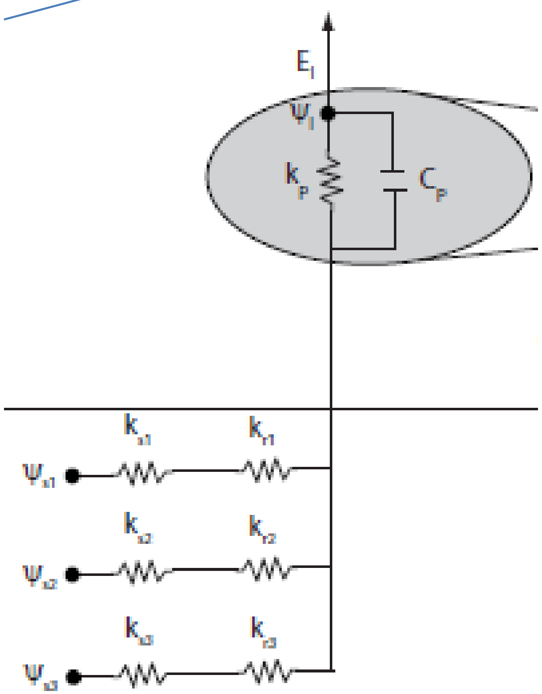



Nepstad et al. (2007) *Ecology*

# Possible components of a hydraulics scheme

(* = required)

| Hydraulic gradients * | Hydraulic effects on stomata* | Variable plant conductivity | Tissue water content (mass balance) |
|---|---|---|---|




Bonan et al. (2014) *GMD*

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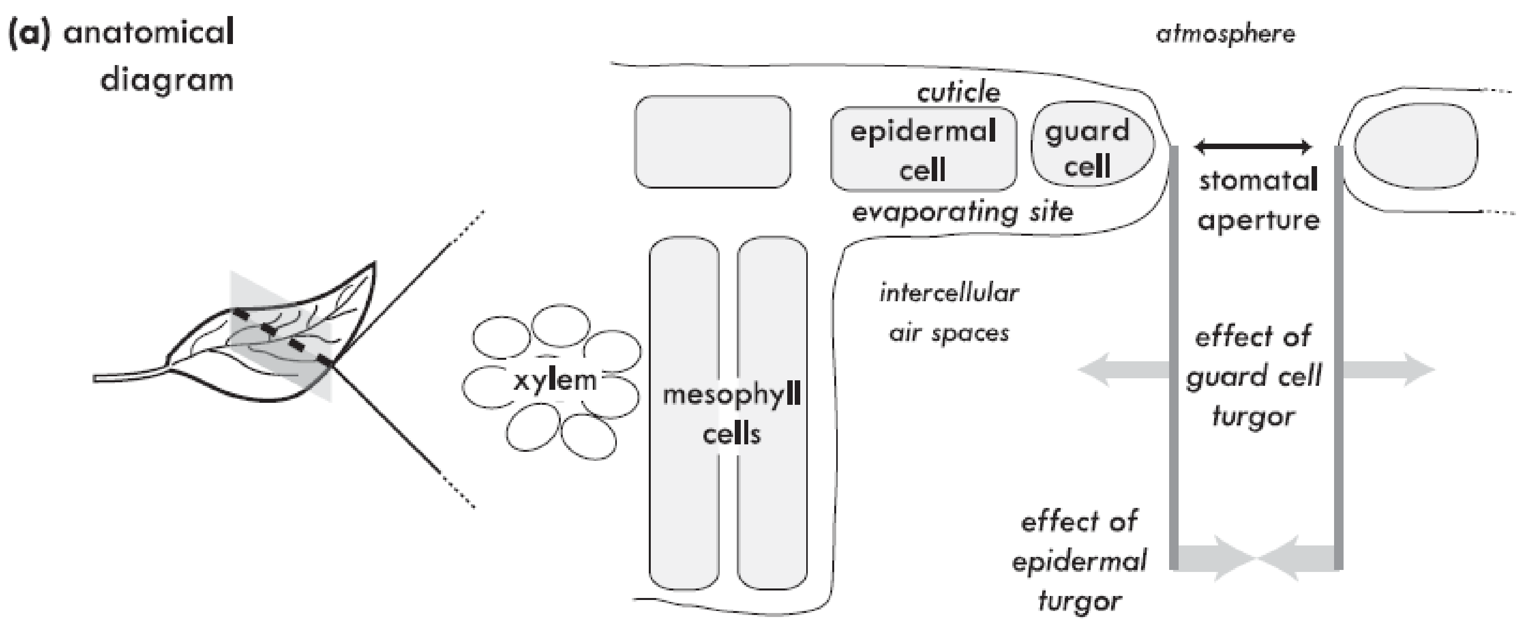


Buckley 2005 *New Phyt*; see also Peak & Mott 2011 *PCE,* Mott & Peak 2013 *PCE*

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| | | | |
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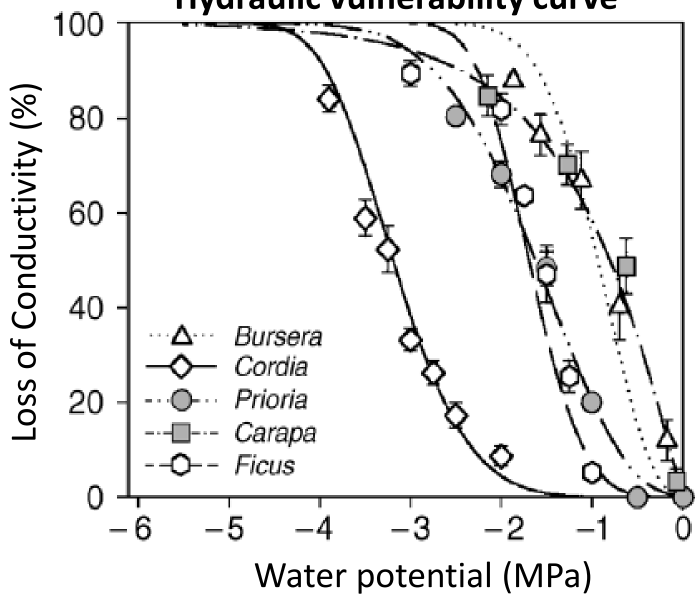
| **Hydraulic gradients *** | **Hydraulic effects on stomata*** | **Variable plant conductivity** | **Tissue water content (mass balance)** |

**Hydraulic vulnerability curve**




Lopez et al. (2005) *Tree Phys*

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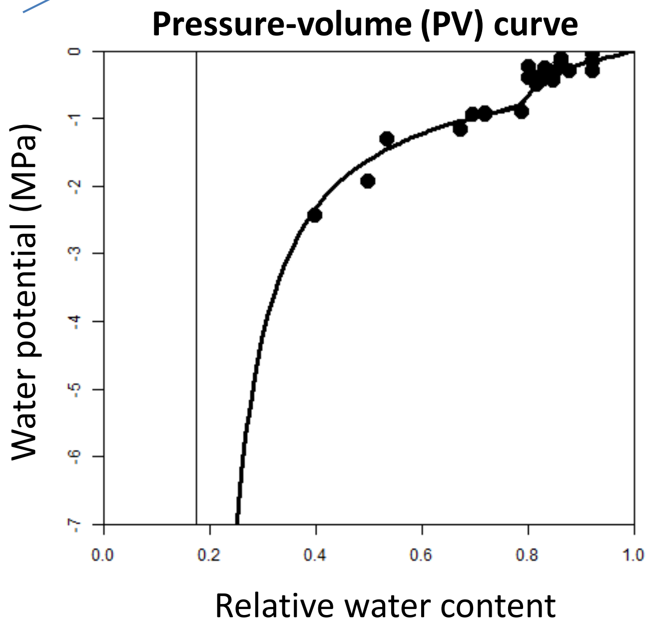


replotted from Tyree et al. (1991) *Plant Phys*

# What hydraulics schemes are out there?

| Model type | Hydraulic gradients | Hydraulic effects on stomata | Variable plant conductivity | Tissue water content (mass balance) | Reference(s) |
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| β (BTRAN) | - | - | - | - | Feddes et al. (1978) |
| SPA-type | ✓ | Isohydric A/gs or A/E | - | implicit | Williams et al. (1996) |
| Hickler-type (LPJ) | ✓ | Isohydric | ✓ | implicit | Hickler et al. (2006) |
| Sperry-type | ✓ | - ($E_{crit}$) | ✓ | explicit | Sperry et al. (1998) |

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| **This model** | ✓ | **continuum of strategies** | ✓ | **explicit** | **Christoffersen et al. in prep** |

# Model structure (Inspired by Sperry et al., 1998)

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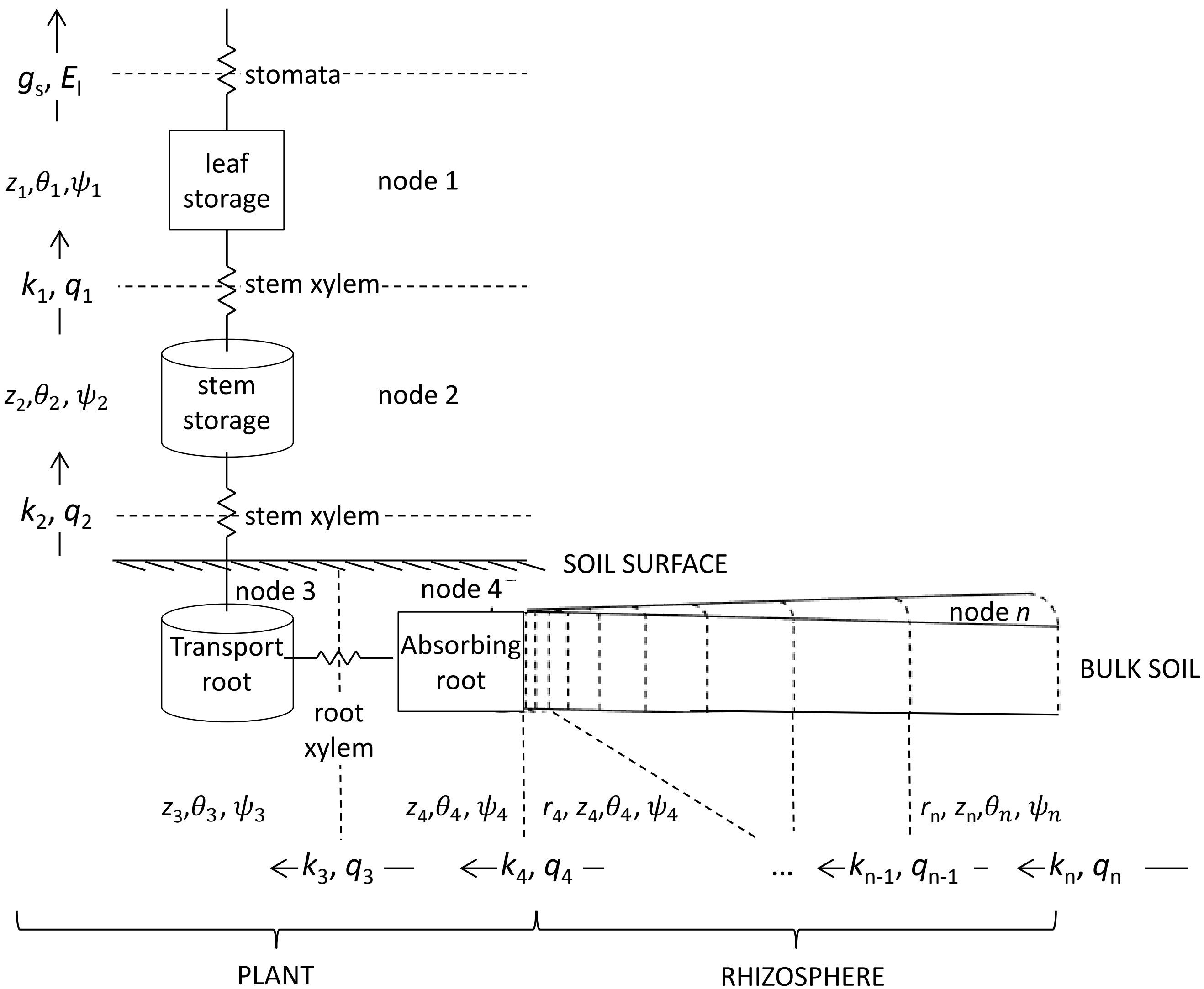

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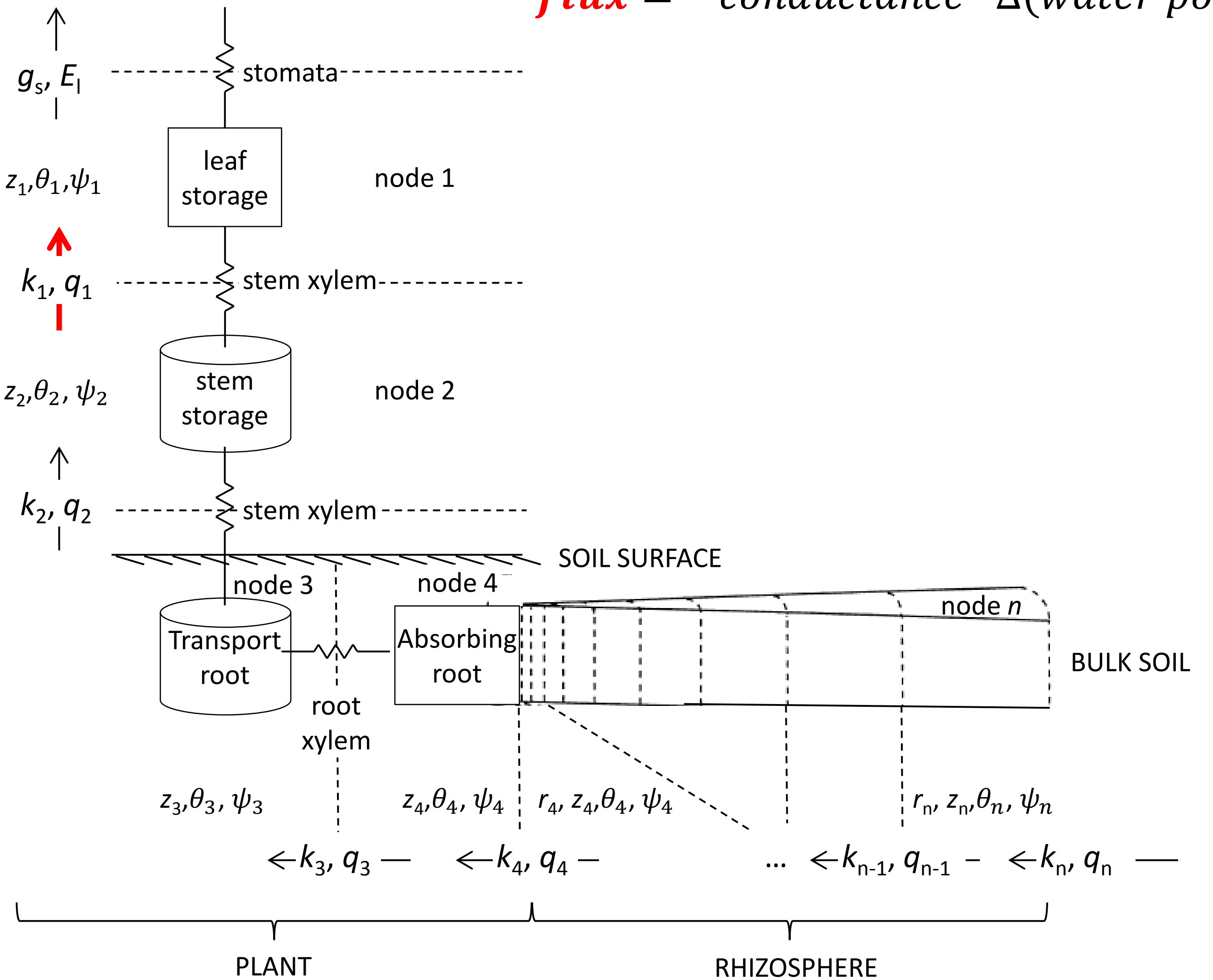

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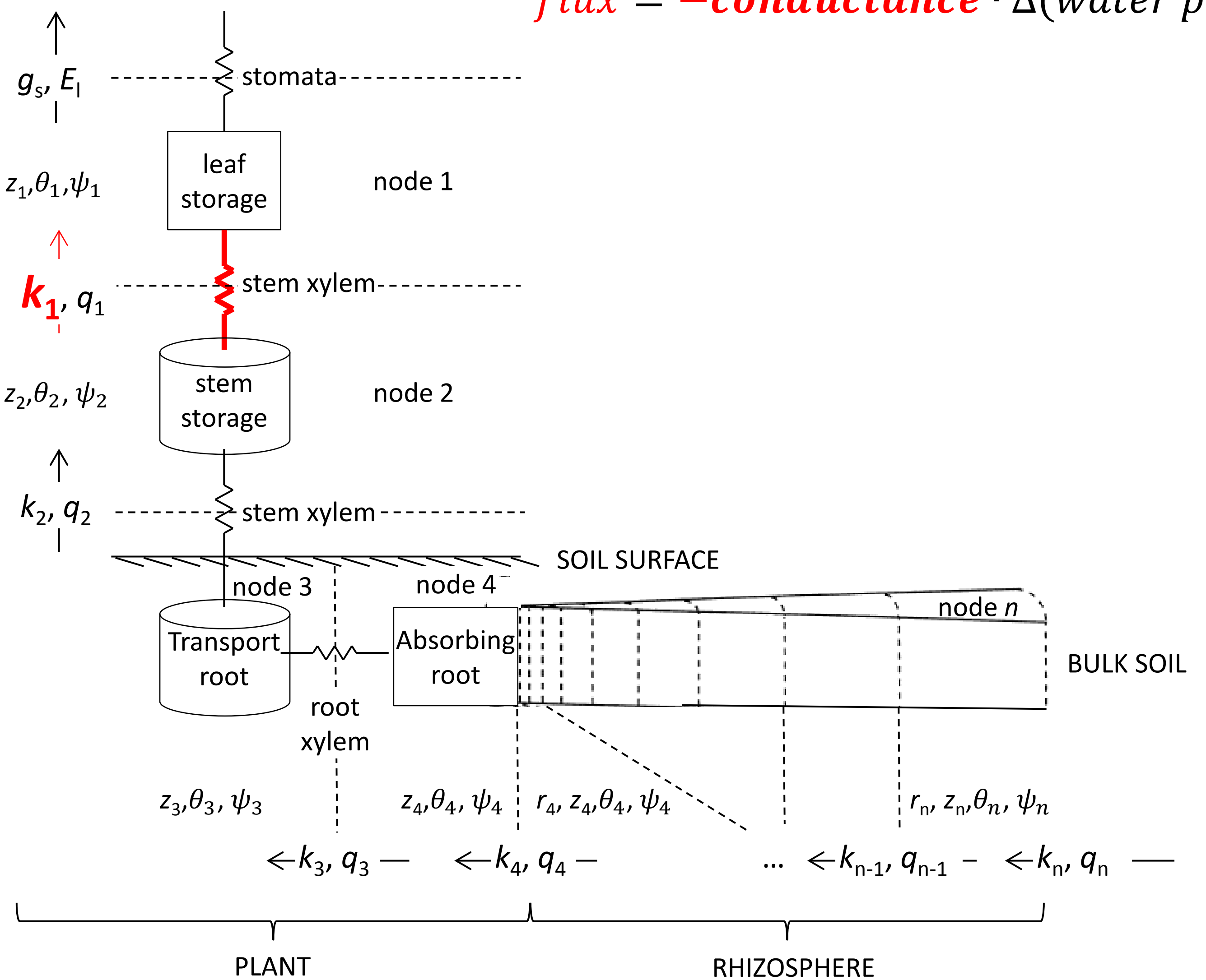

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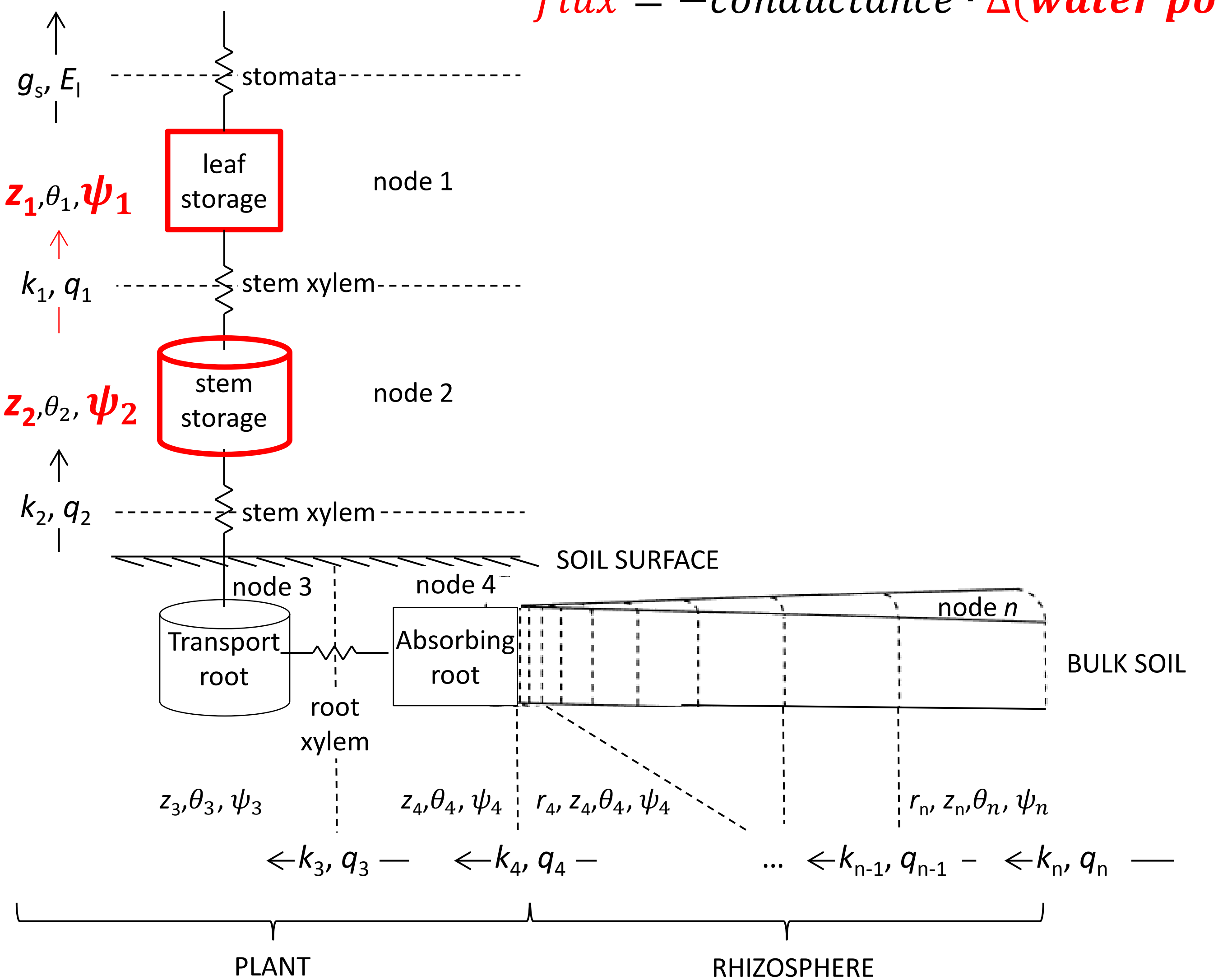

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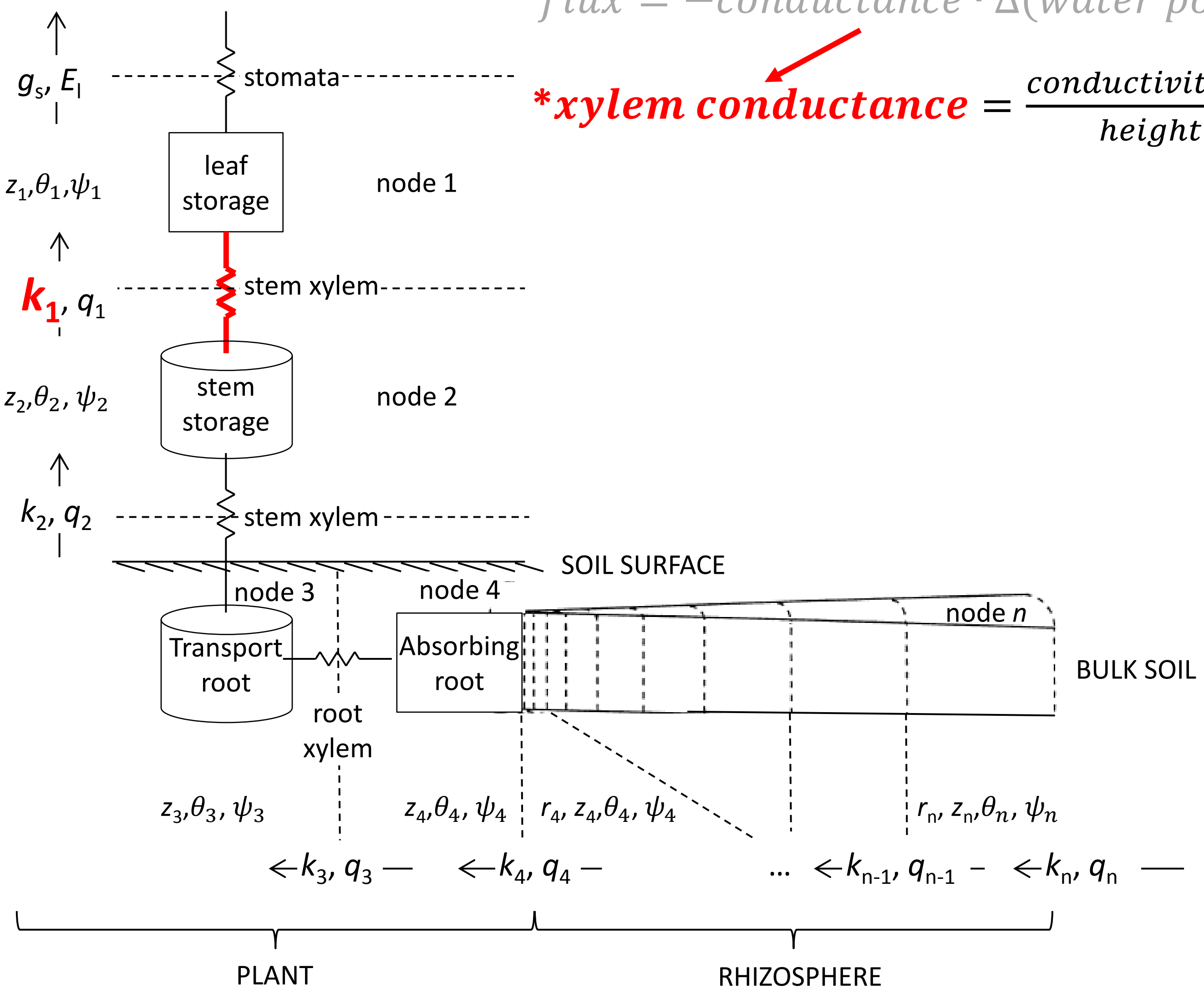

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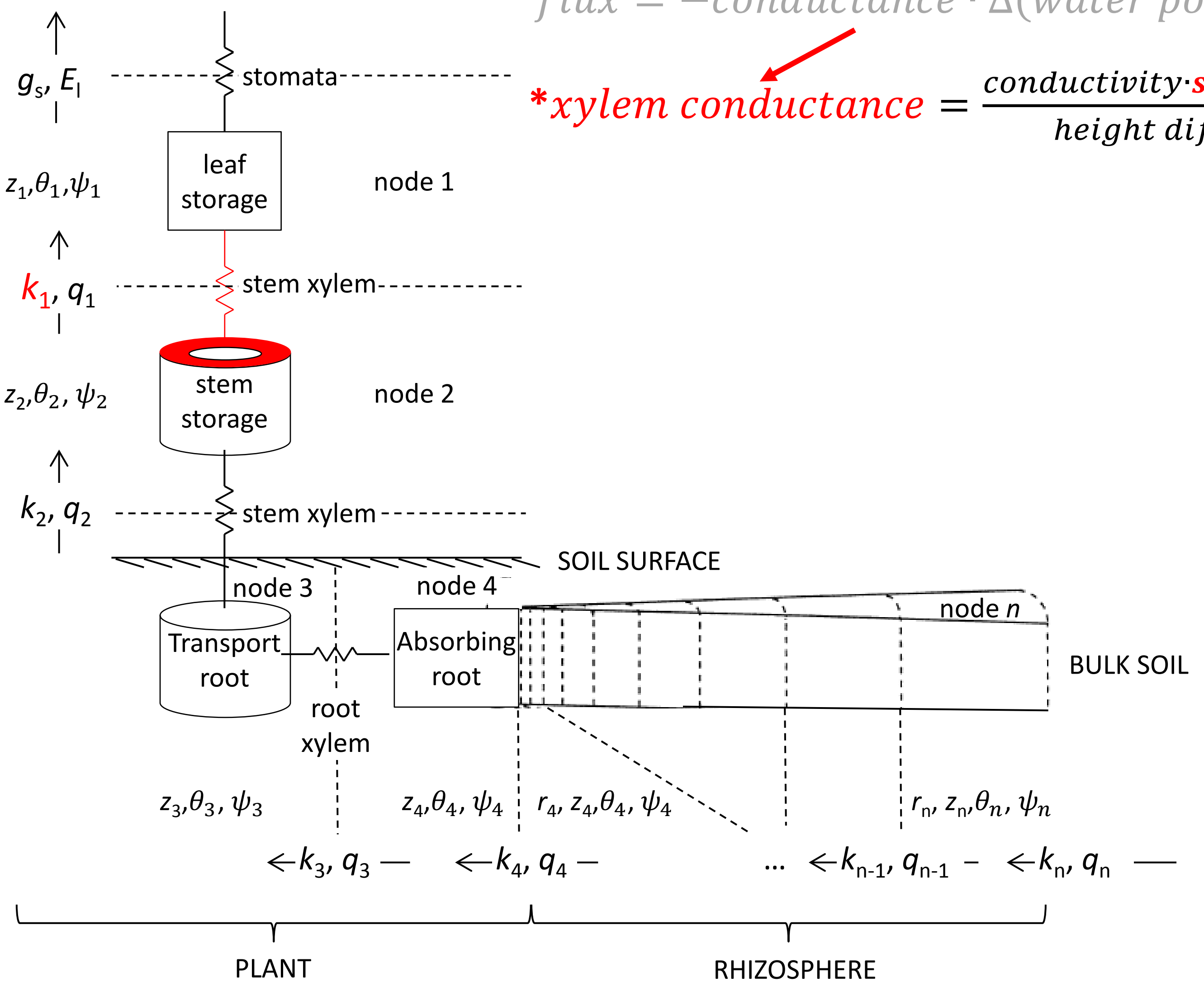

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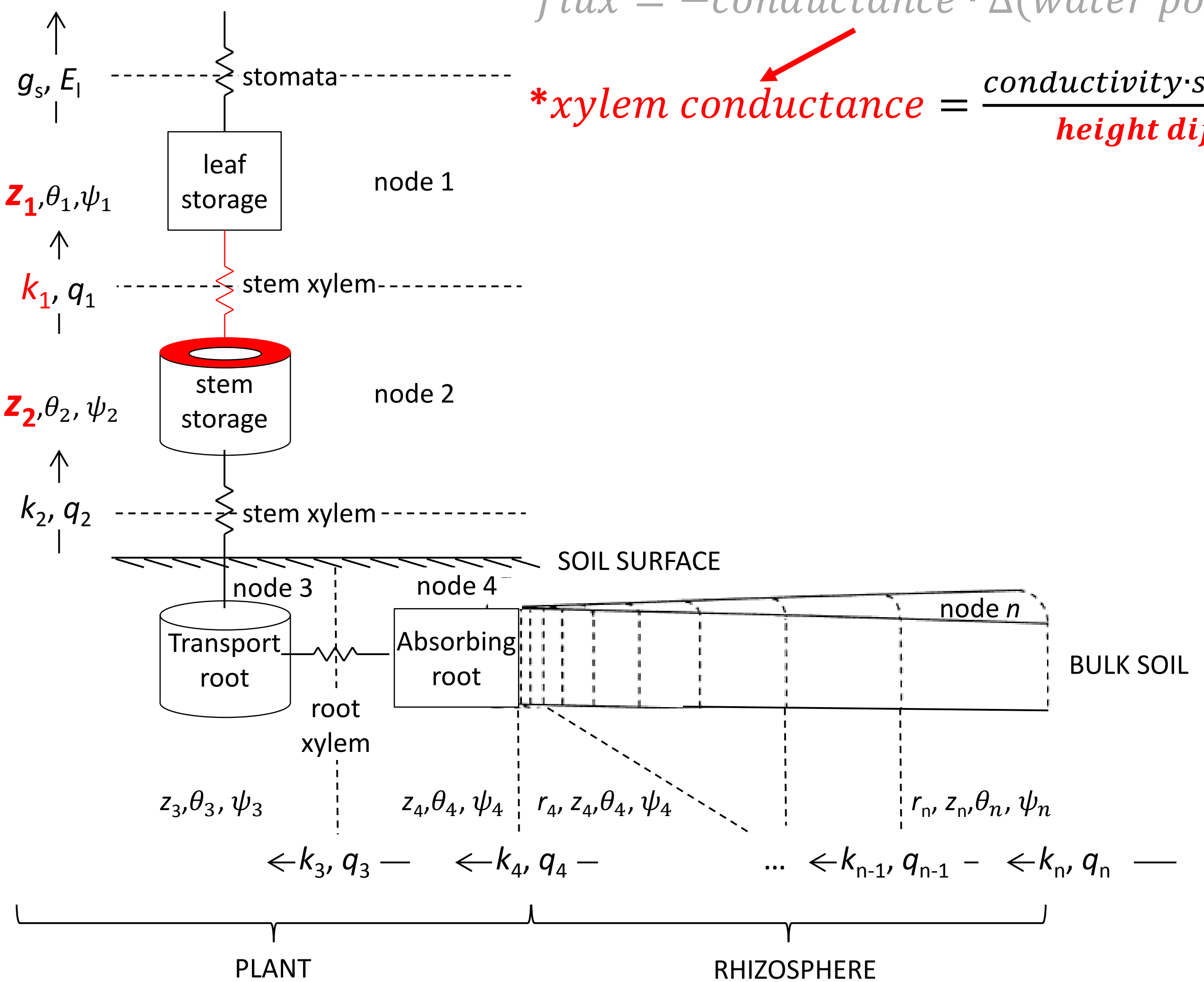

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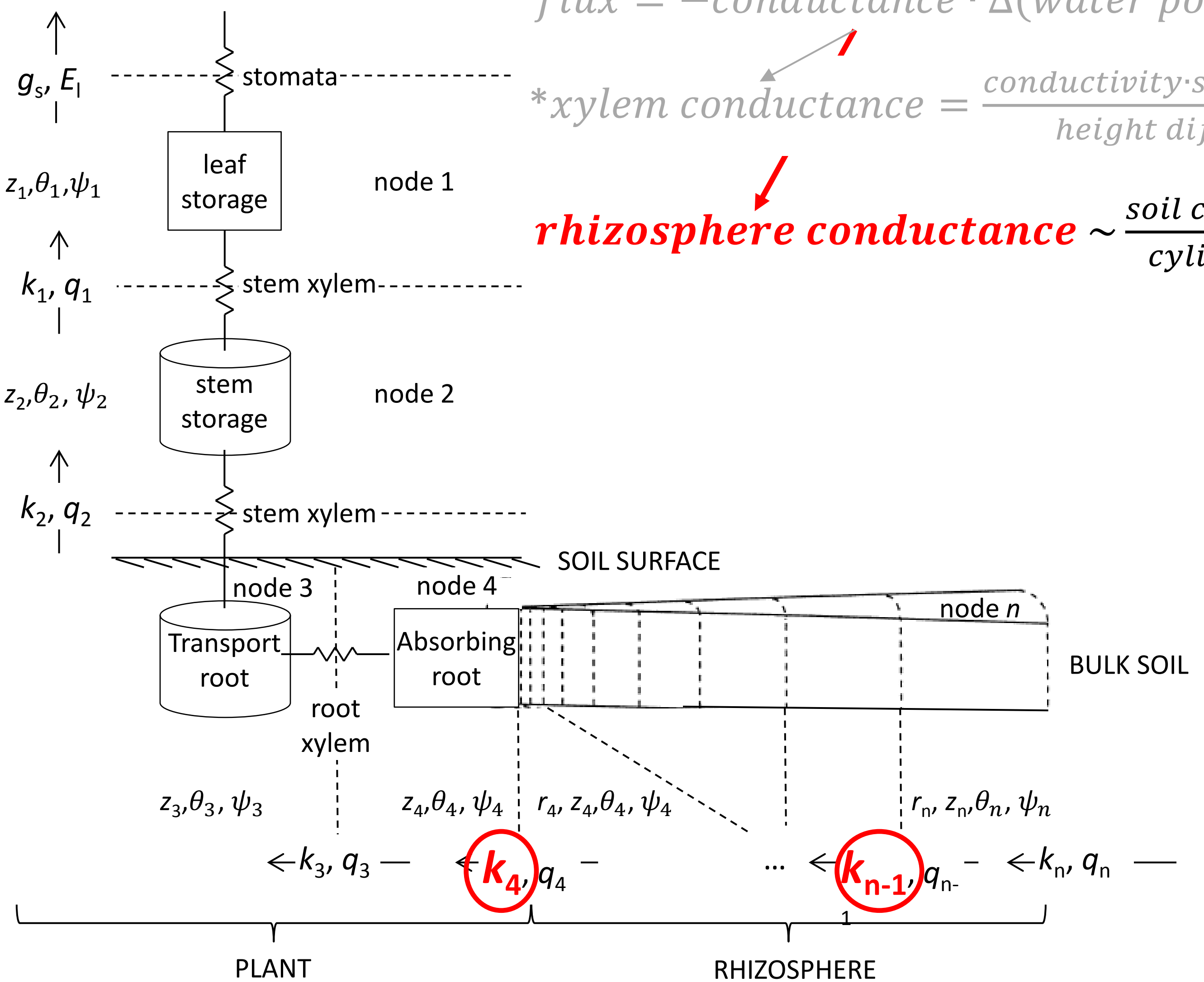

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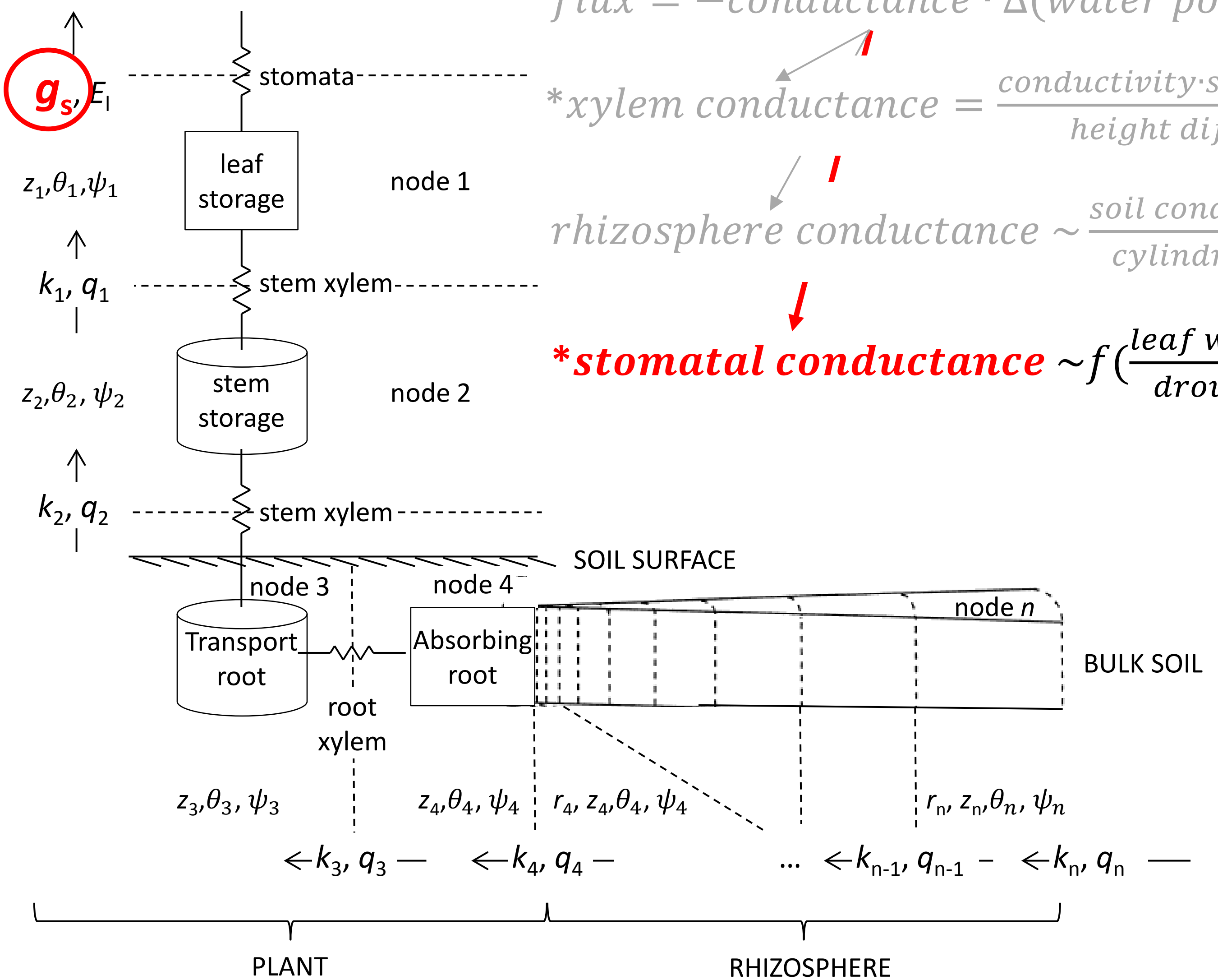
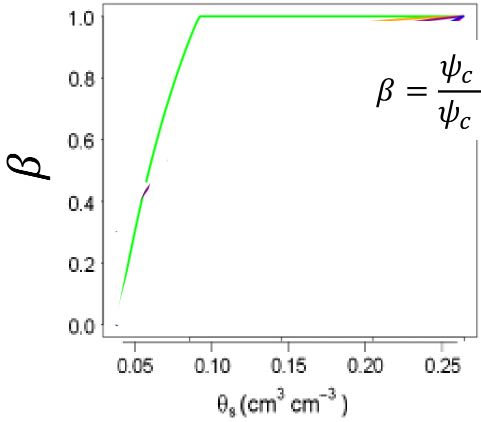


# What about stomatal conductance? Modified BTRAN

**OLD**




$$\beta = \frac{\psi_c - \psi_i}{\psi_c - \psi_o}$$

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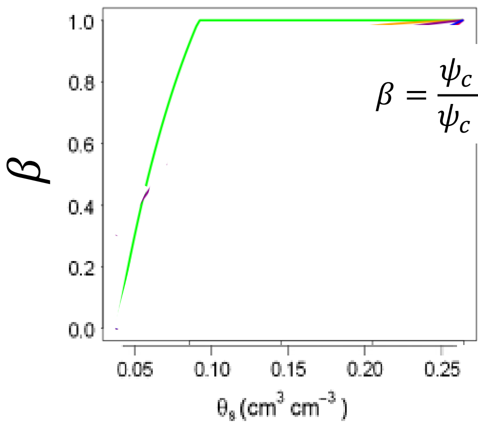


$$\beta = \frac{\psi_c - \psi_i}{\psi_c - \psi_o}$$

- $\boldsymbol{\psi_c}$ :
  - soil water potential at stomatal closure
- $\boldsymbol{\psi_o}$ :
  - soil water potential at beginning of stomatal closure
- $\boldsymbol{\psi_i}$ :
  - soil water potential
- Dependent on PFT, soil properties, and soil moisture only

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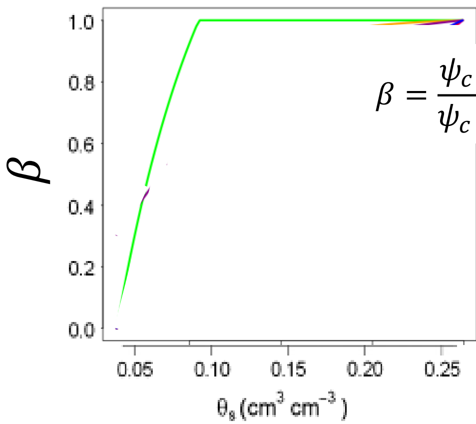


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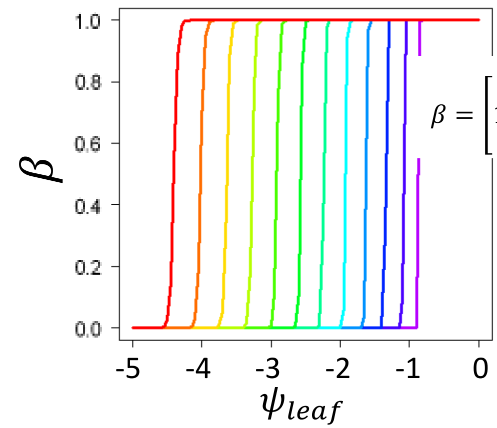


$$\beta = \left[1 + \left(\frac{\psi_{leaf}}{\phantom{x}}\right)^a\right]^{-1}$$

- $\boldsymbol{\psi_{leaf}}$ is a function of:
  - Atmospheric demand
  - Light environment
  - Water supply
  - Plant height
  - Plant traits: conductance, P50, turgor loss point
  - → Integrated measure of **EVERYTHING**

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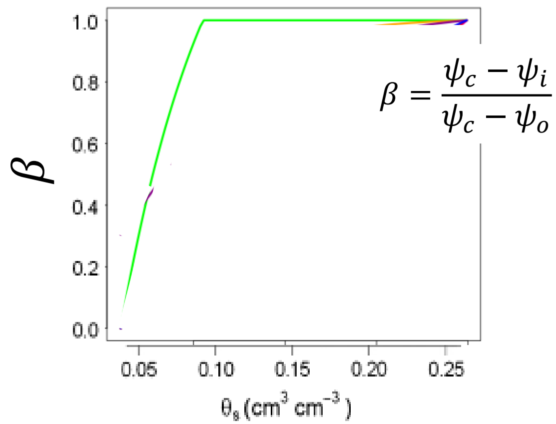


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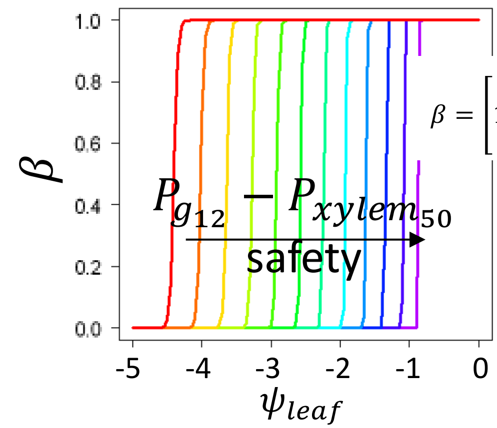


$$\beta = \left[1 + \left(\frac{\psi_{leaf}}{P_{g_{12}} - P_{xylem_{50}}}\right)^a\right]^{-1}$$

Skelton et al. (2015) *PNAS*

- $\boldsymbol{\psi_{leaf}}$ is a function of:
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  - Plant height
  - Plant traits: conductance, P50, turgor loss point
  - → Integrated measure of **EVERYTHING**
- $P_{g_{12}}$: $\boldsymbol{\psi_{leaf}}$ where $g_s$ is 12% of the maximum
  - Degree of safety
  - Isohydry ←→ Anisohydry continuum

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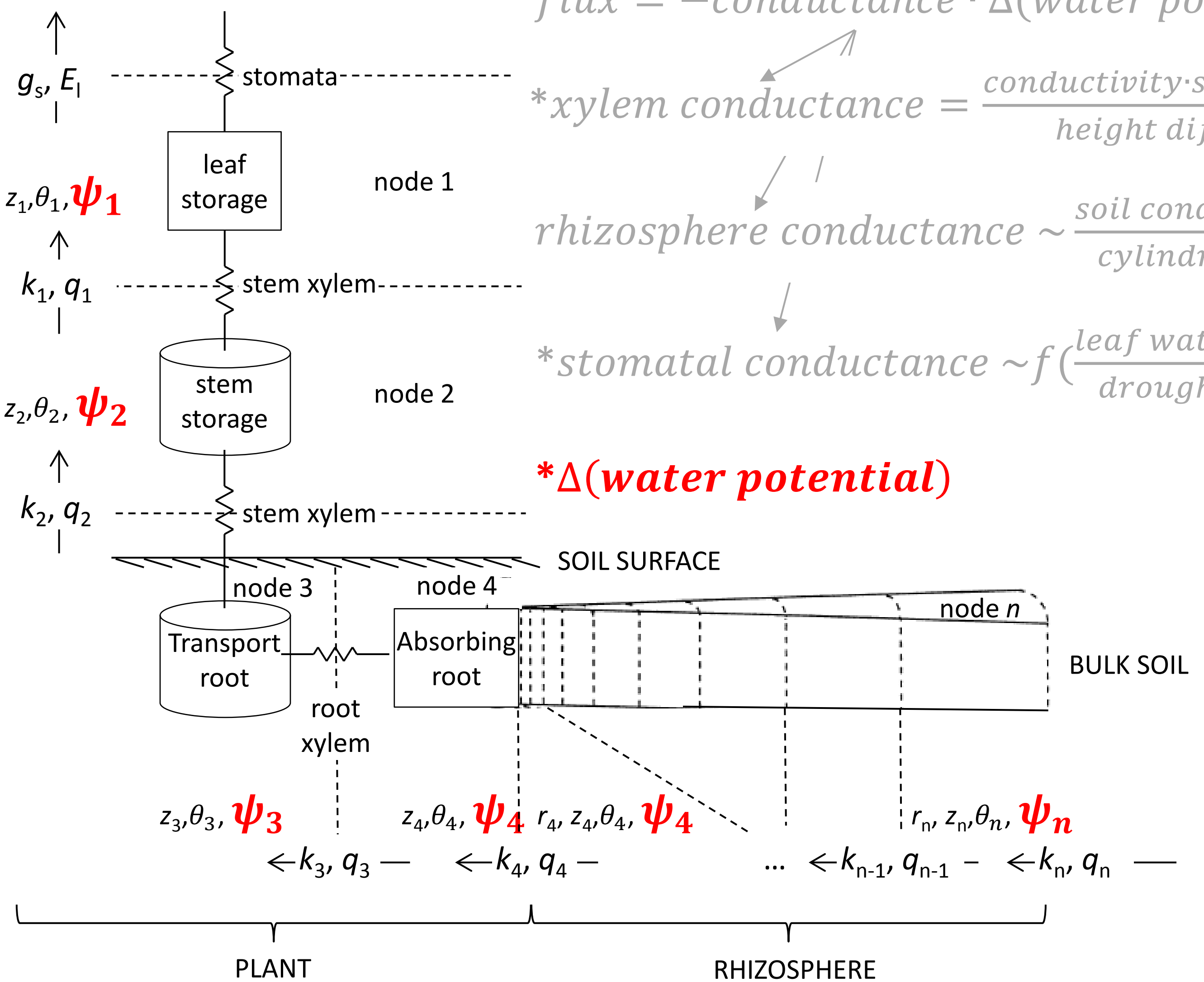

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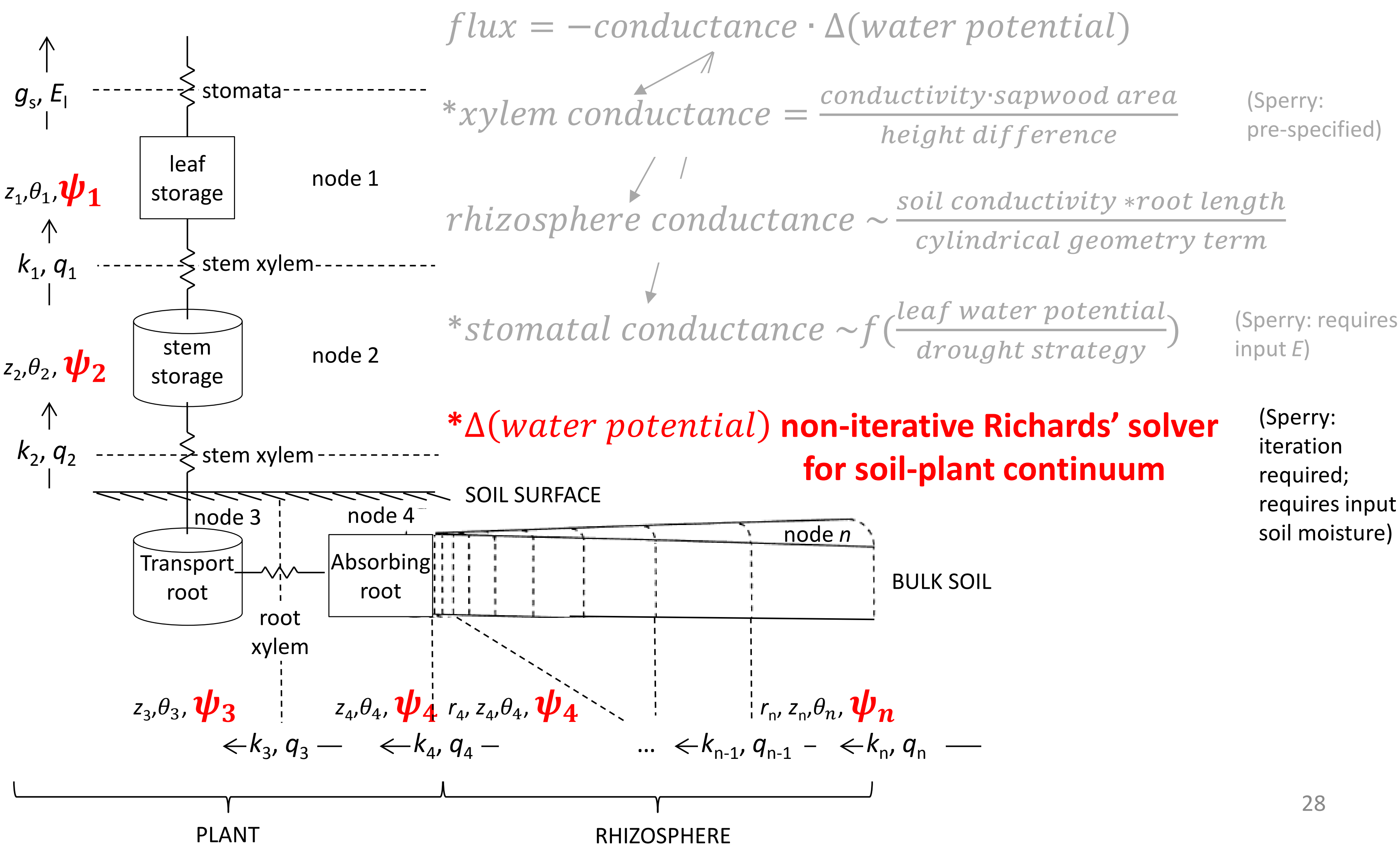
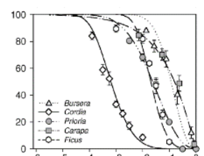


# Richards' Numerical Solution

- Option 1: Water potential (ψ)-based solution: **iteration necessary** (potentially computationally expensive)

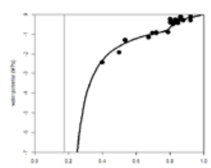
- Option 2: Water mass (θ)-based solution: **no iteration needed*** (as in CLM SoilHydrologyMod)
  - Linearize (1st order Taylor expansion) about $\partial\theta$

$$\frac{dk_{ij}}{d\psi_{ij}}, k_{ij} \sim f(\psi_{ij})$$




Continuously differentiable vulnerability curves

$$\frac{d\psi_{ij}}{d\theta_{ij}}, \psi_{ij} \sim f(\theta_{ij})$$



Continuously differentiable PV curves

* Iterative timestep reduction if water budget not balanced (Ross 2003)

# Hydraulic Scheme Testbed: Trait Forest Simulator (TFS)

(Fyllas et al. 2014 GMD)

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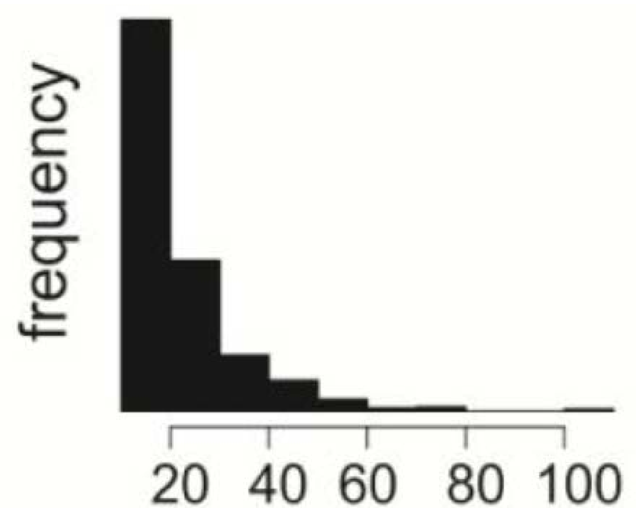
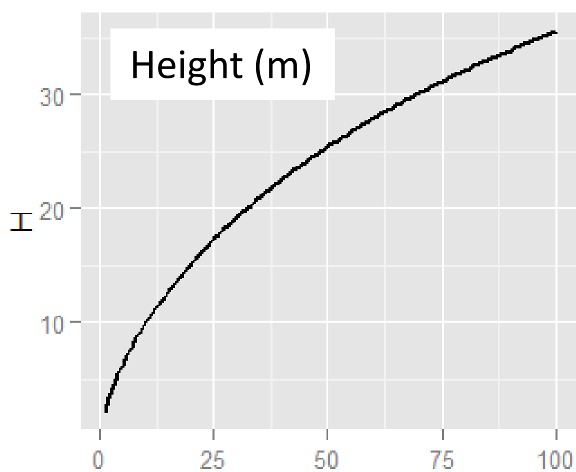
(Fyllas et al. 2014 GMD)

- **Individual tree model**
  - DBH, height, sapwood, crown allometry




Tree diameter (cm)

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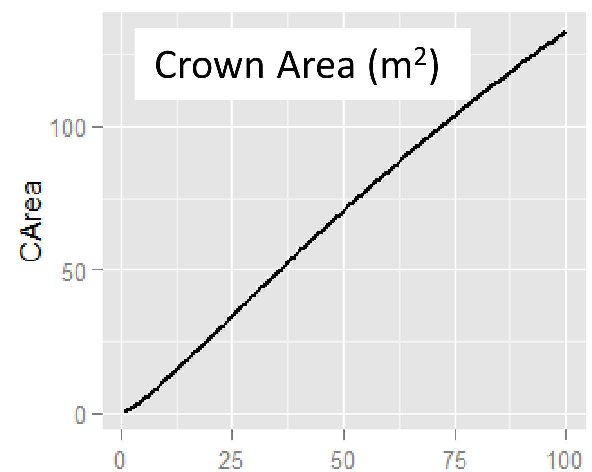


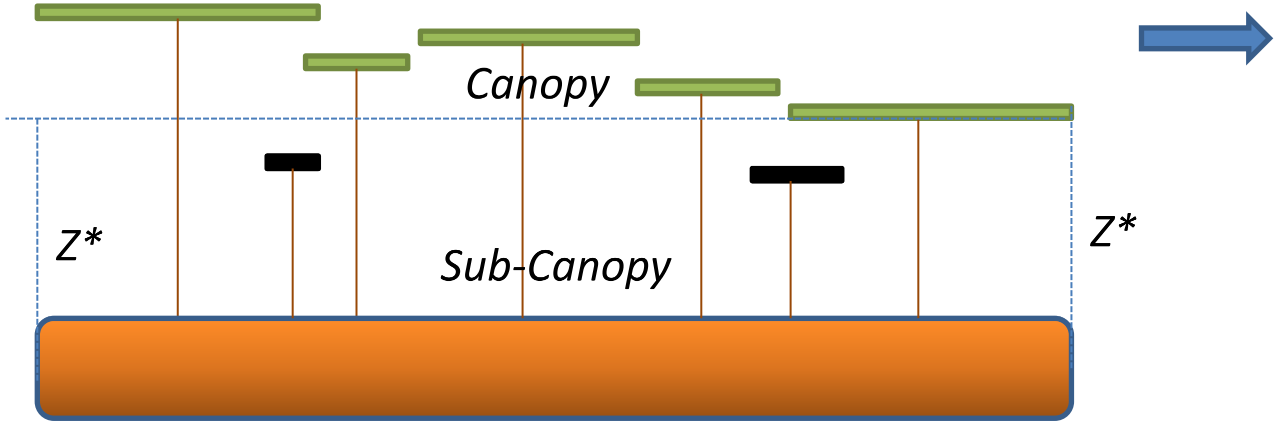

Tree diameter (cm)

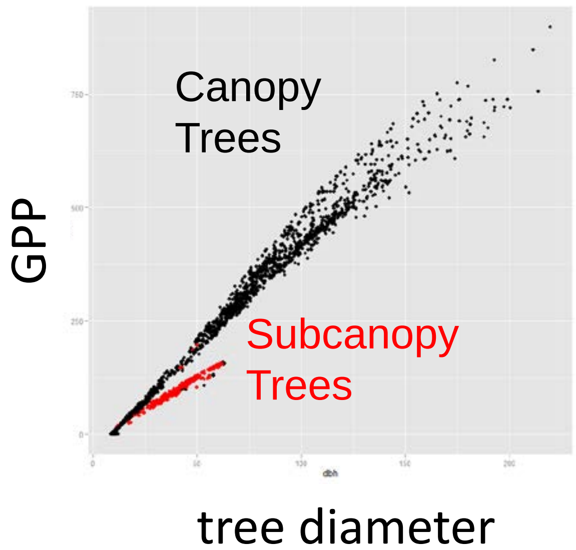
# Hydraulic Scheme Testbed: Trait Forest Simulator (TFS)

(Fyllas et al. 2014 GMD)

- **Light competition/tessellation**
  - Spatially implicit (computationally tractable)

Flat-top crowns
Perfect Plasticity Approximation (PPA)



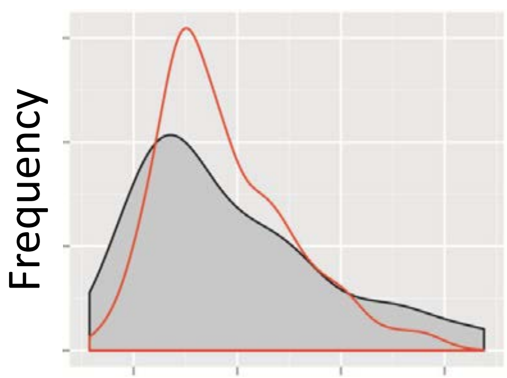

Purves et al. (2007) *PLoS One*; Bohlman & Pacala (2012) *J Ecol*

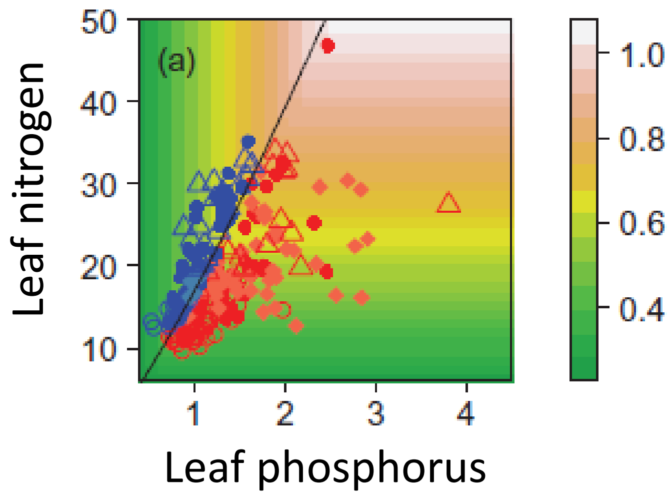
# Hydraulic Scheme Testbed: Trait Forest Simulator (TFS)

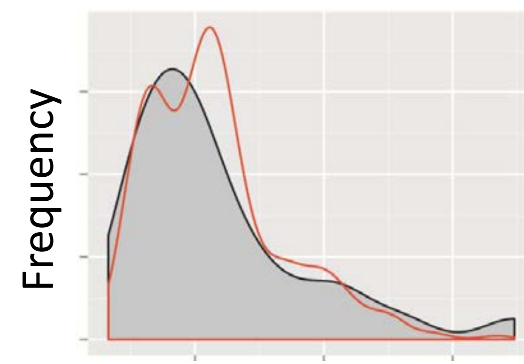
(Fyllas et al. 2014 GMD)

- **4 traits:** wood density, leaf mass per area, leaf nitrogen, leaf phosphorus

Input trait distribution (e.g., leaf nitrogen) → Physiology as function of traits (e.g., Vcmax) → Output distribution of physiological params




Domingues et al. (2010) *PCE*

# Hydraulic Scheme Testbed: Trait Forest Simulator (TFS)

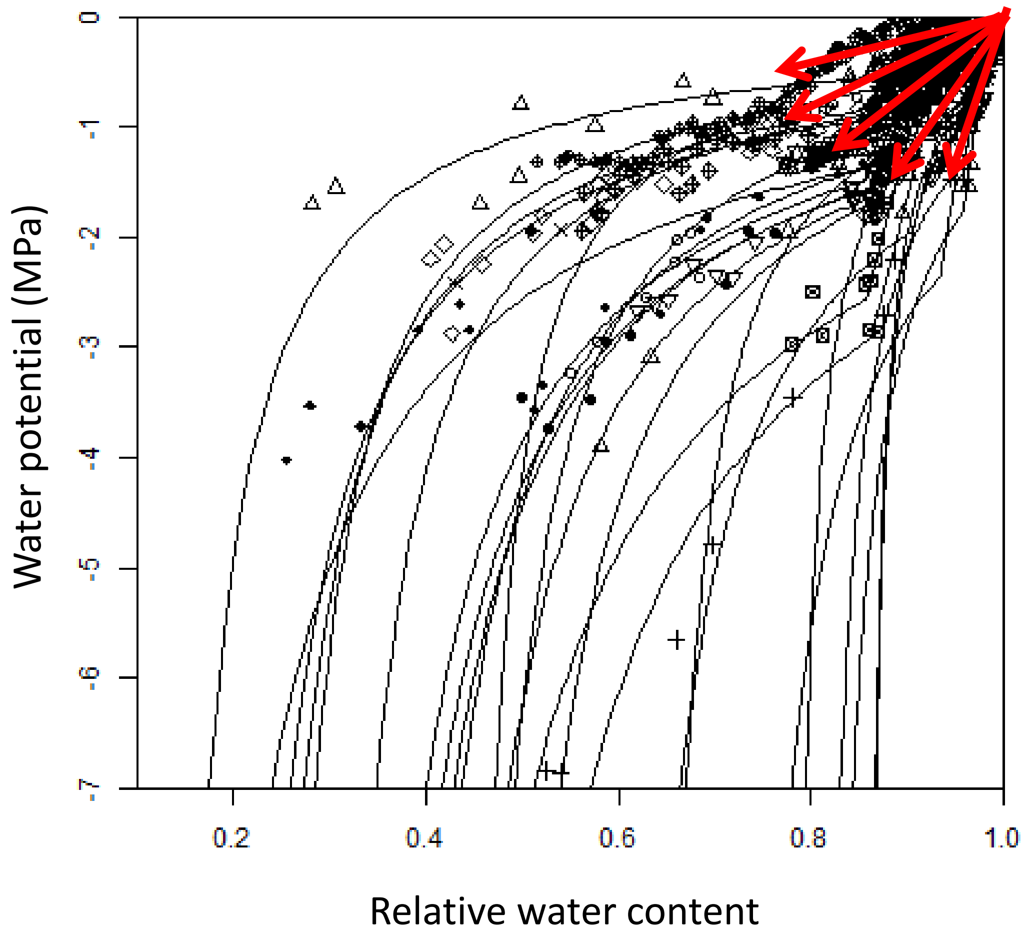
(Fyllas et al. 2014 GMD)

- **Similar to CLM(ED), except**:
  - Individual-, not cohort-based
  - Trait distributions, not successional stages
  - Some differences in canopy biophysics


# ARE TRAITS USEFUL?
# PARAMETERIZING HYDRAULICS SCHEME

# Case study: Hydraulic Capacitance

**Literature meta-analysis:**
**32 sapwood PV curves across 31 species, pantropical**




Christoffersen et al. in prep

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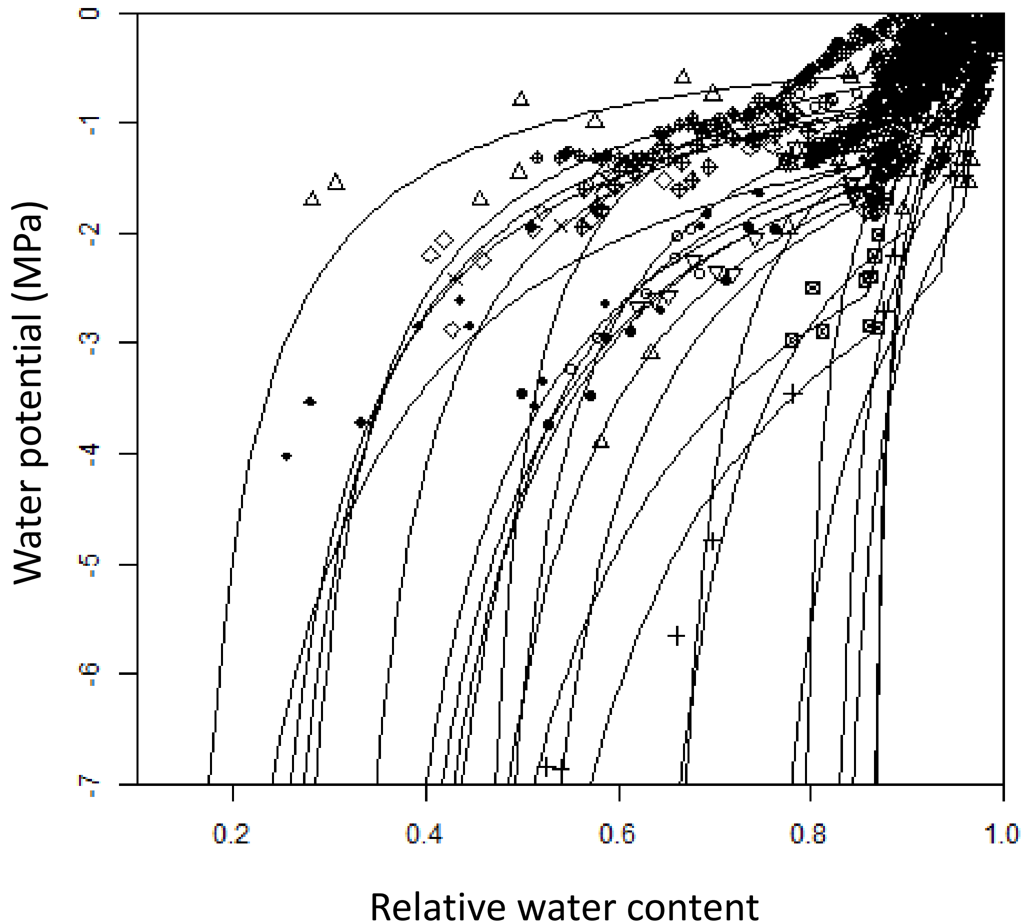


**Mechanistic parameters describing a PV curve:**

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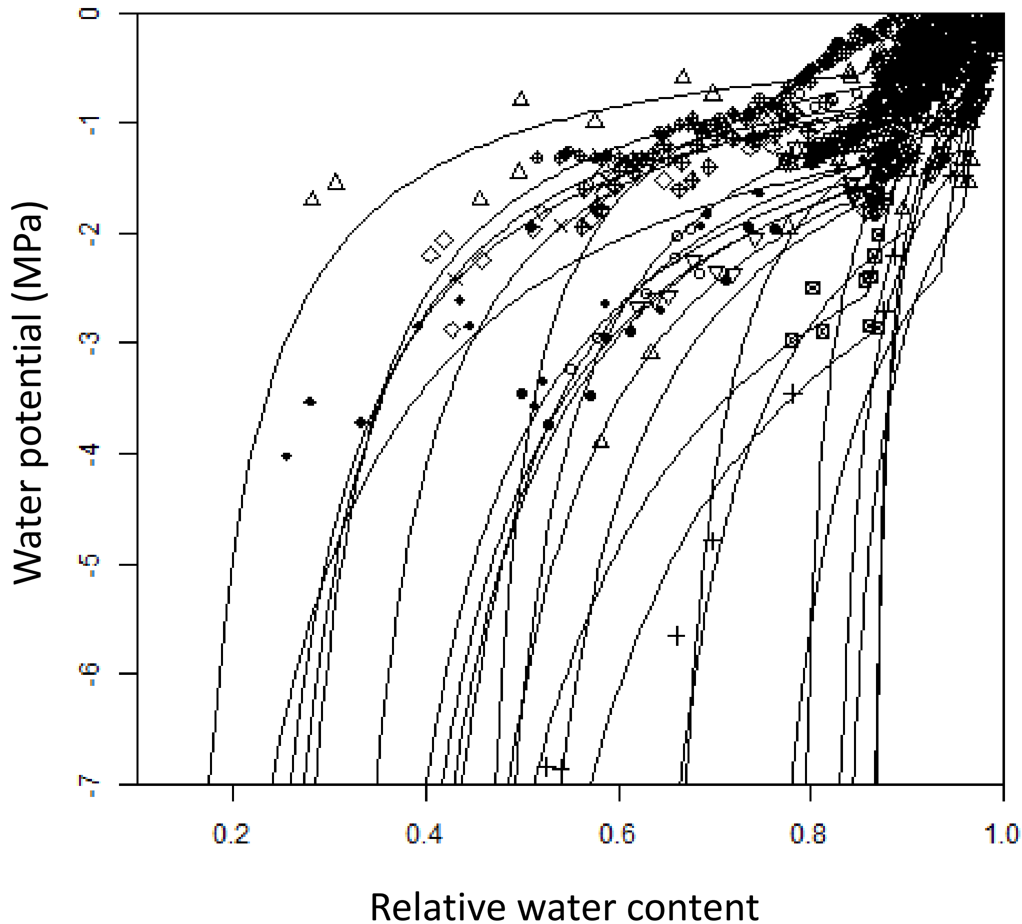


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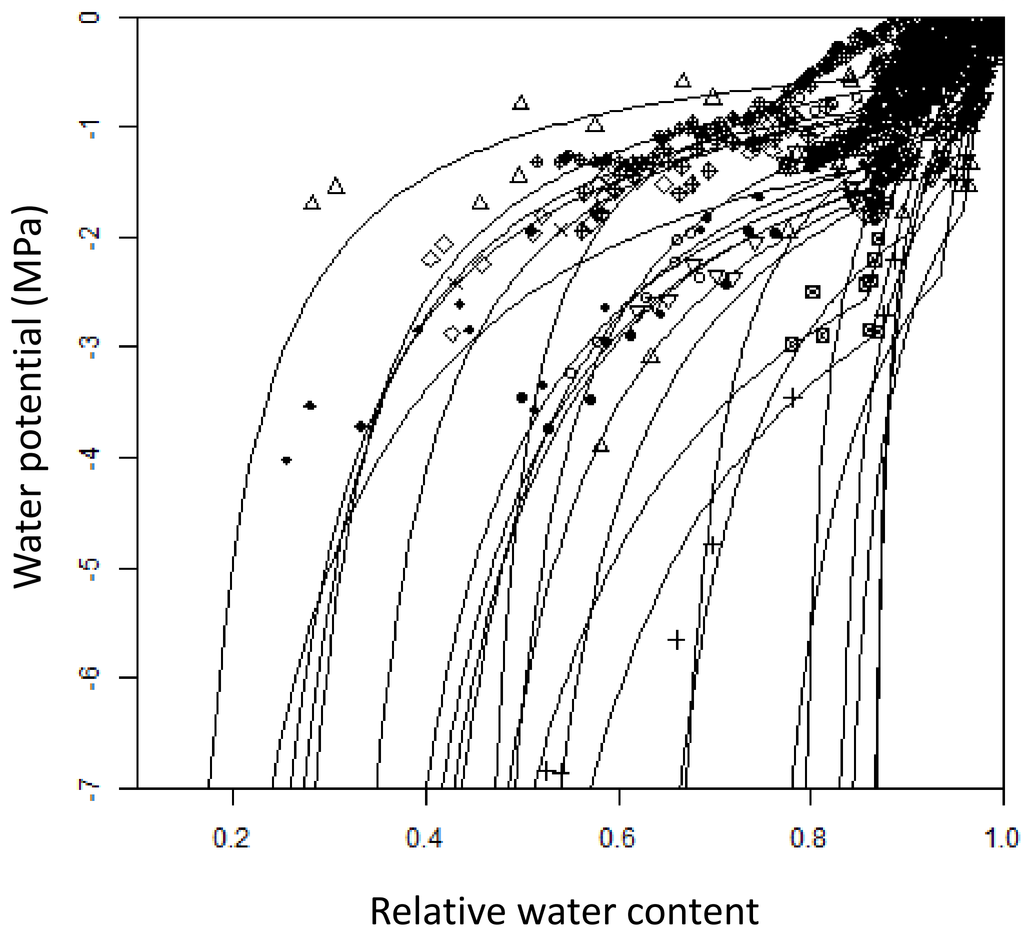


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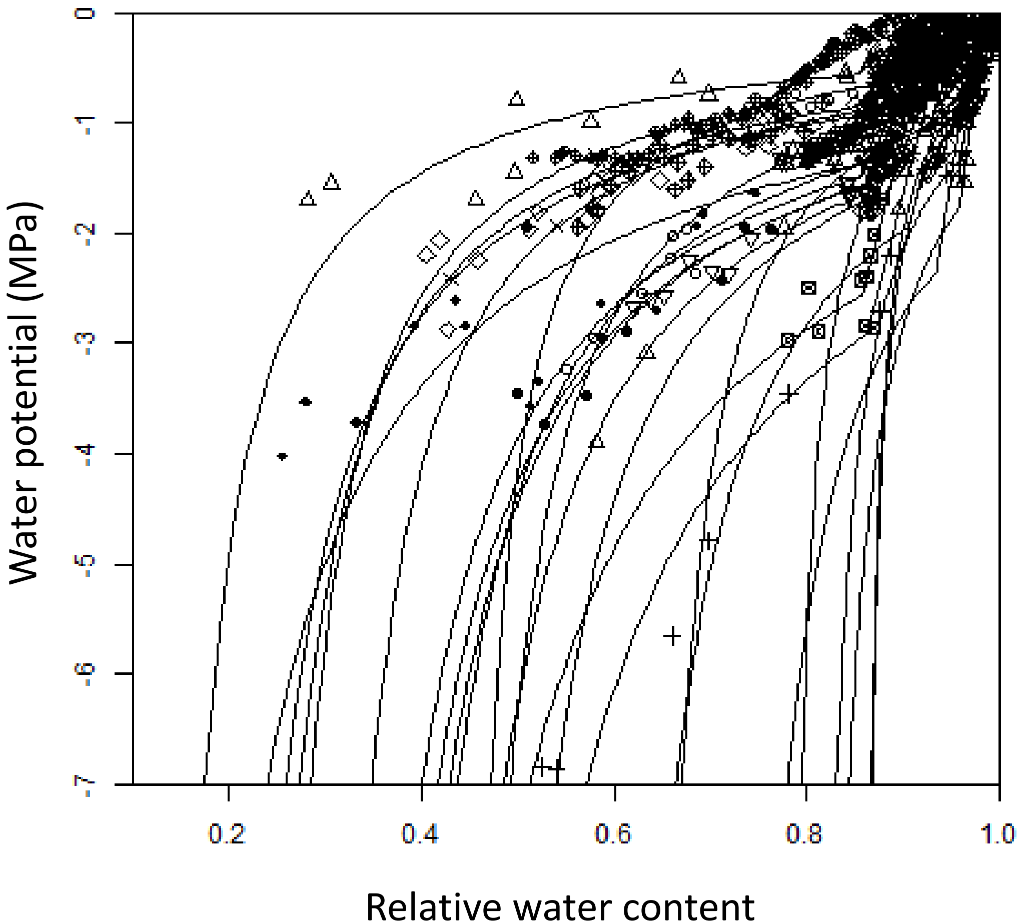


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available water before losing turgor
**1-$RWC_{tlp}$**

Christoffersen et al. in prep

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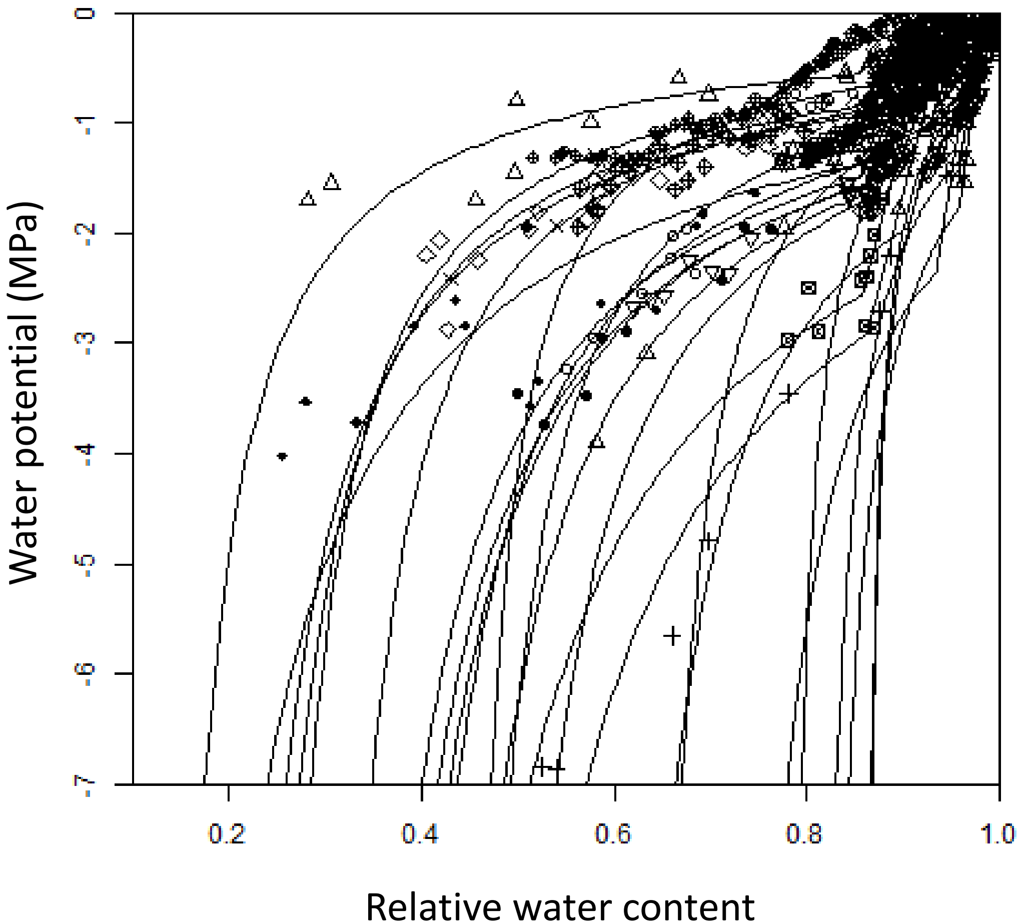
**Literature meta-analysis:**
**32 sapwood PV curves across 31 species, pantropical**




**Mechanistic parameters describing a PV curve:**

osmotic potential $\pi_o$
(cell saltiness)

bulk elastic modulus $\varepsilon$
(cell stiffness)

available water before losing turgor
**1-$RWC_{tlp}$**

## Is this functional diversity described by a single trait axis?

Christoffersen et al. in prep

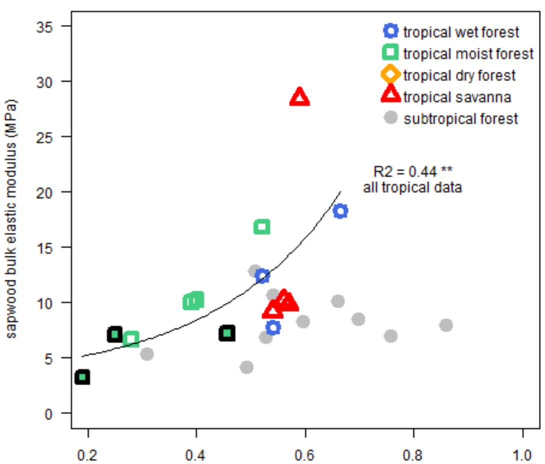
# Yes! *WD* explains coordinated variation among sapwood PV params in the tropics

** = $p < 0.01$, * = $p < 0.05$

excluding subtropical data

$\varepsilon$

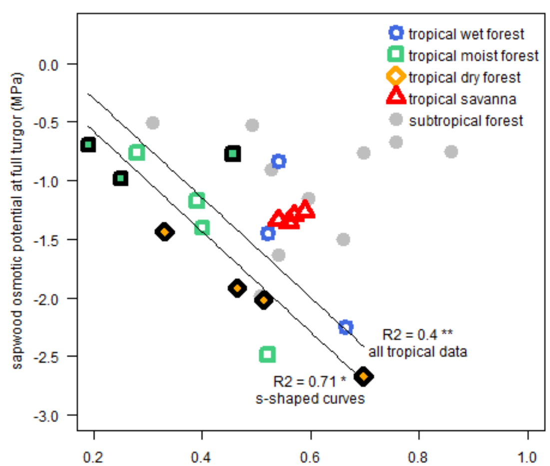
(cell stiffness)




Wood density (g cm$^{-3}$)

$\pi_o$

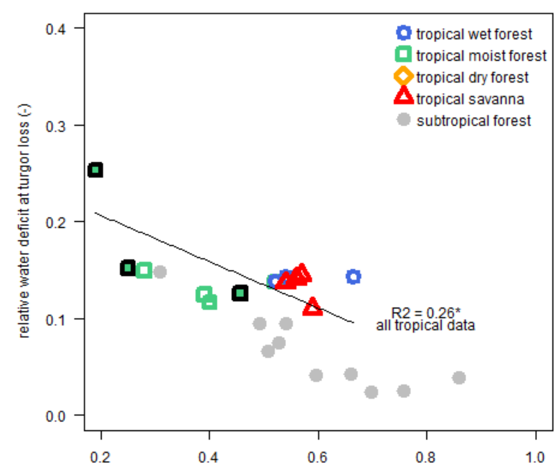
(cell saltiness)




Wood density (g cm$^{-3}$)

1-$RWC_{tlp}$

(where cells lose turgor)




Wood density (g cm$^{-3}$)

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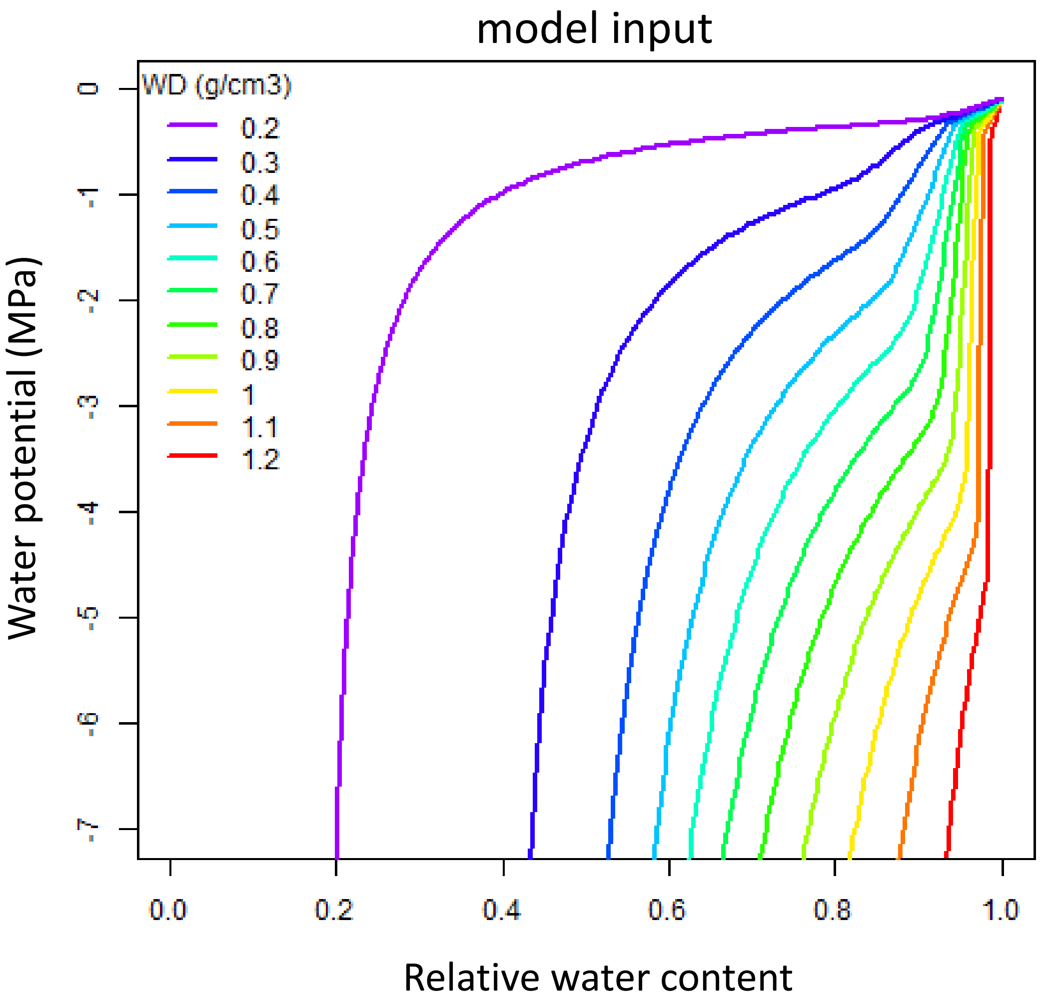
# Resultant parameter inputs to hydraulics scheme

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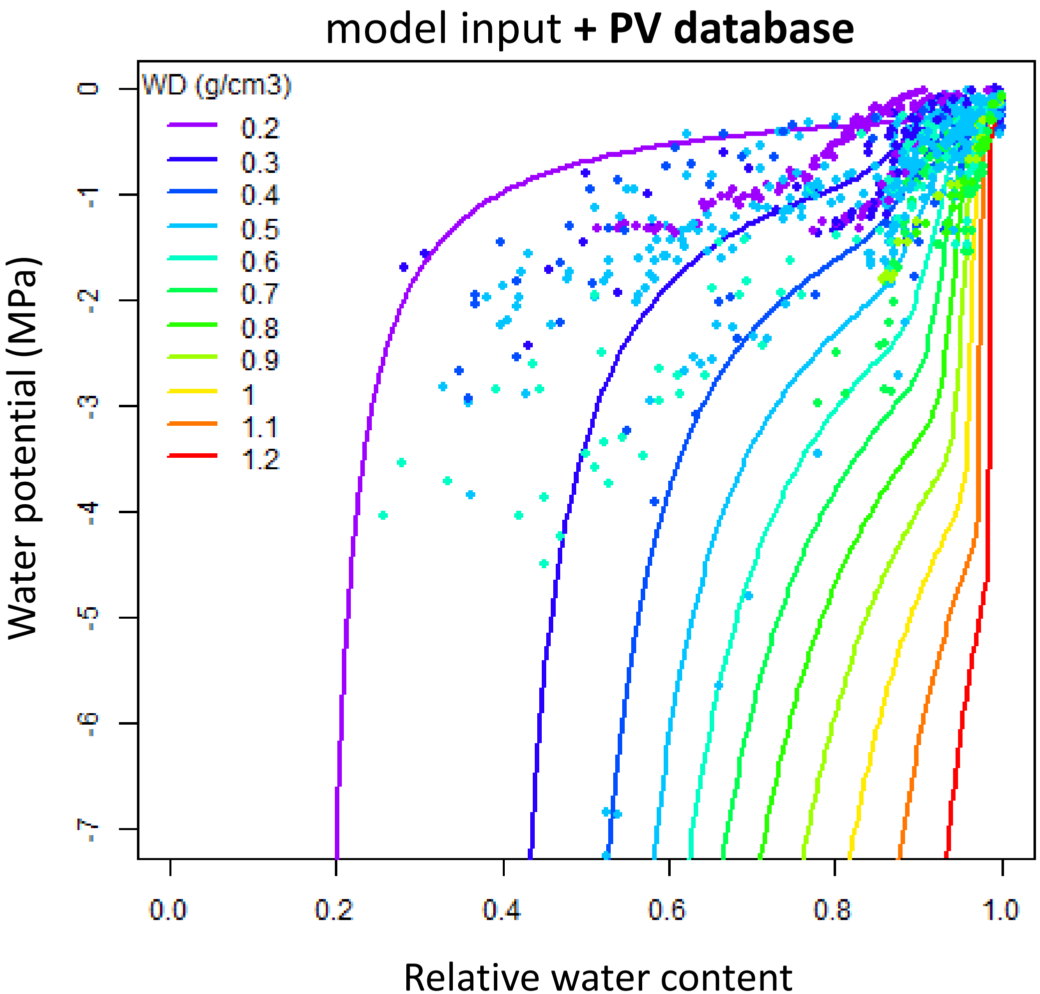
# Resultant parameter inputs to hydraulics scheme

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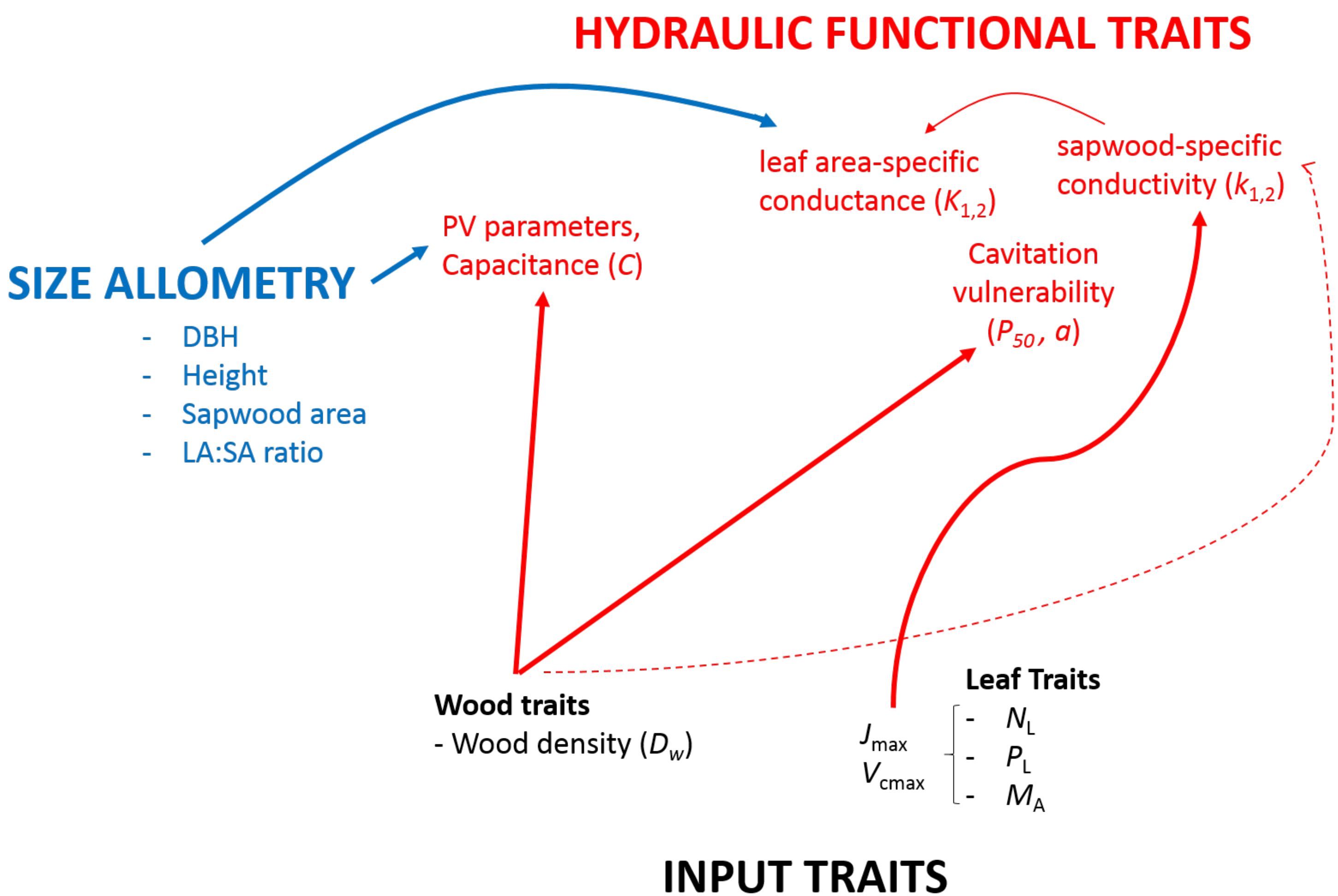
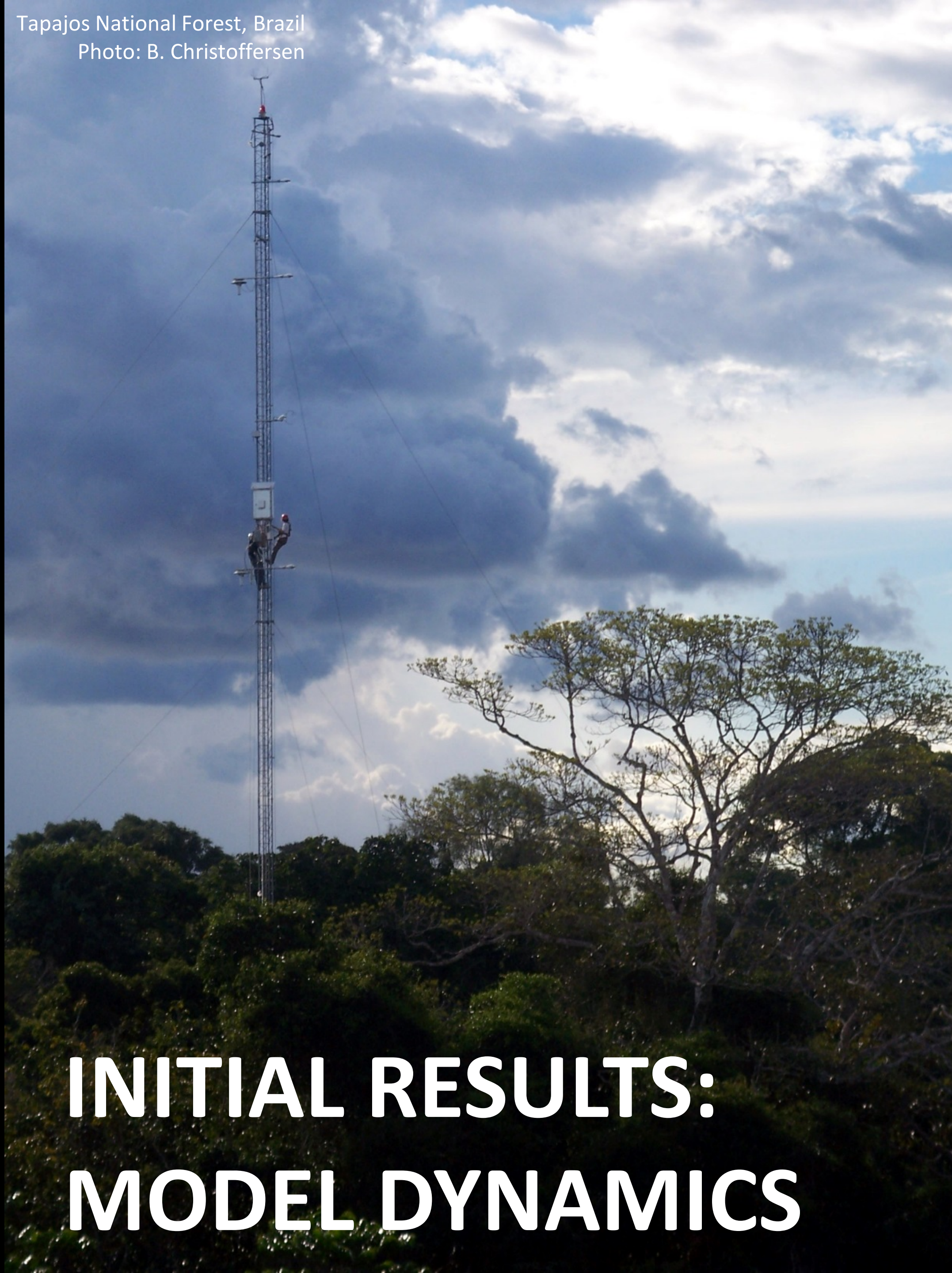
# Meta-analysis used to parameterize rest of model (tropics focus)

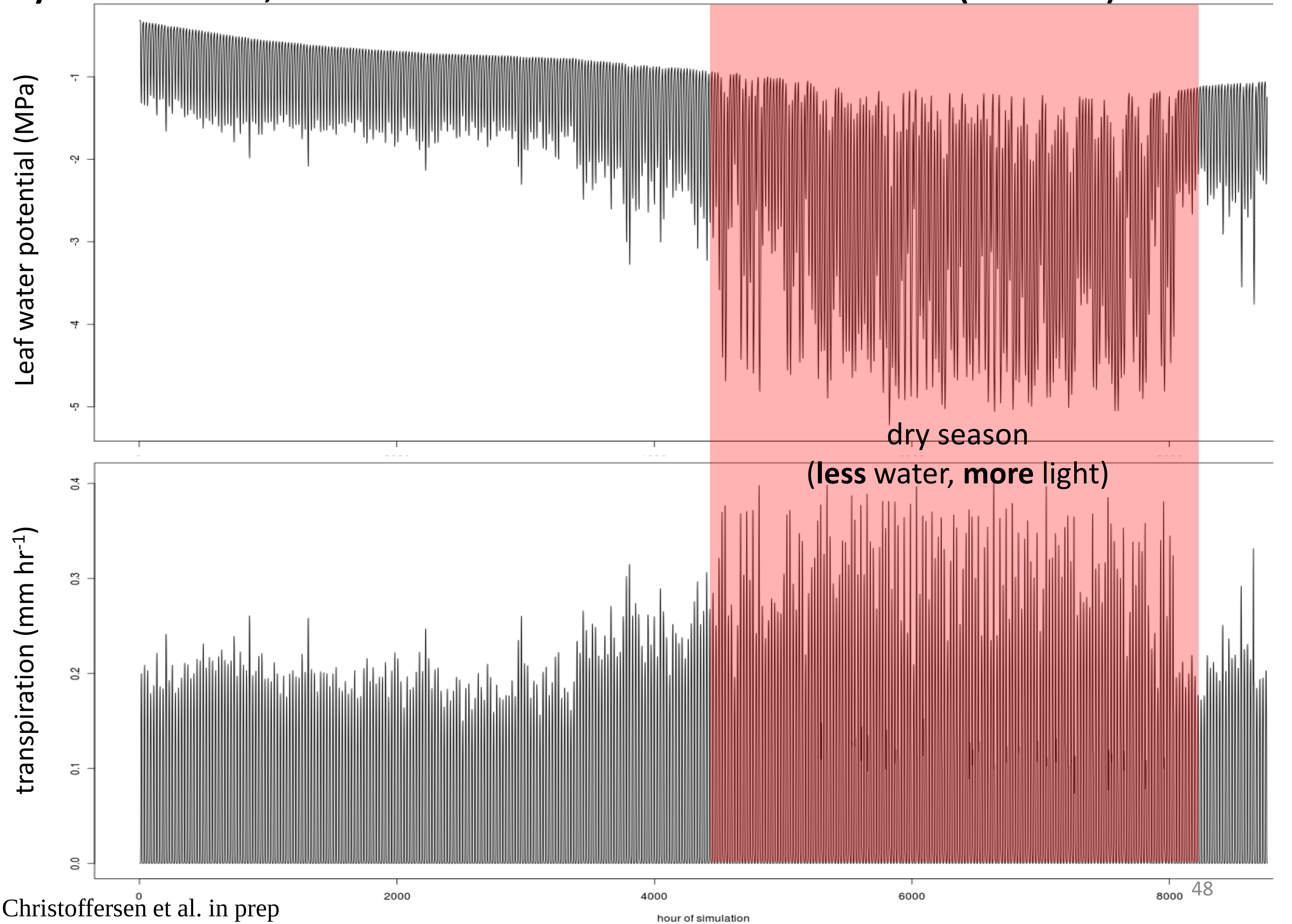




Tapajos National Forest, Brazil
Photo: B. Christoffersen

# INITIAL RESULTS: MODEL DYNAMICS

# 1-year simulation, 60cm DBH individual tree in Eastern Amazon (Caxiuana)

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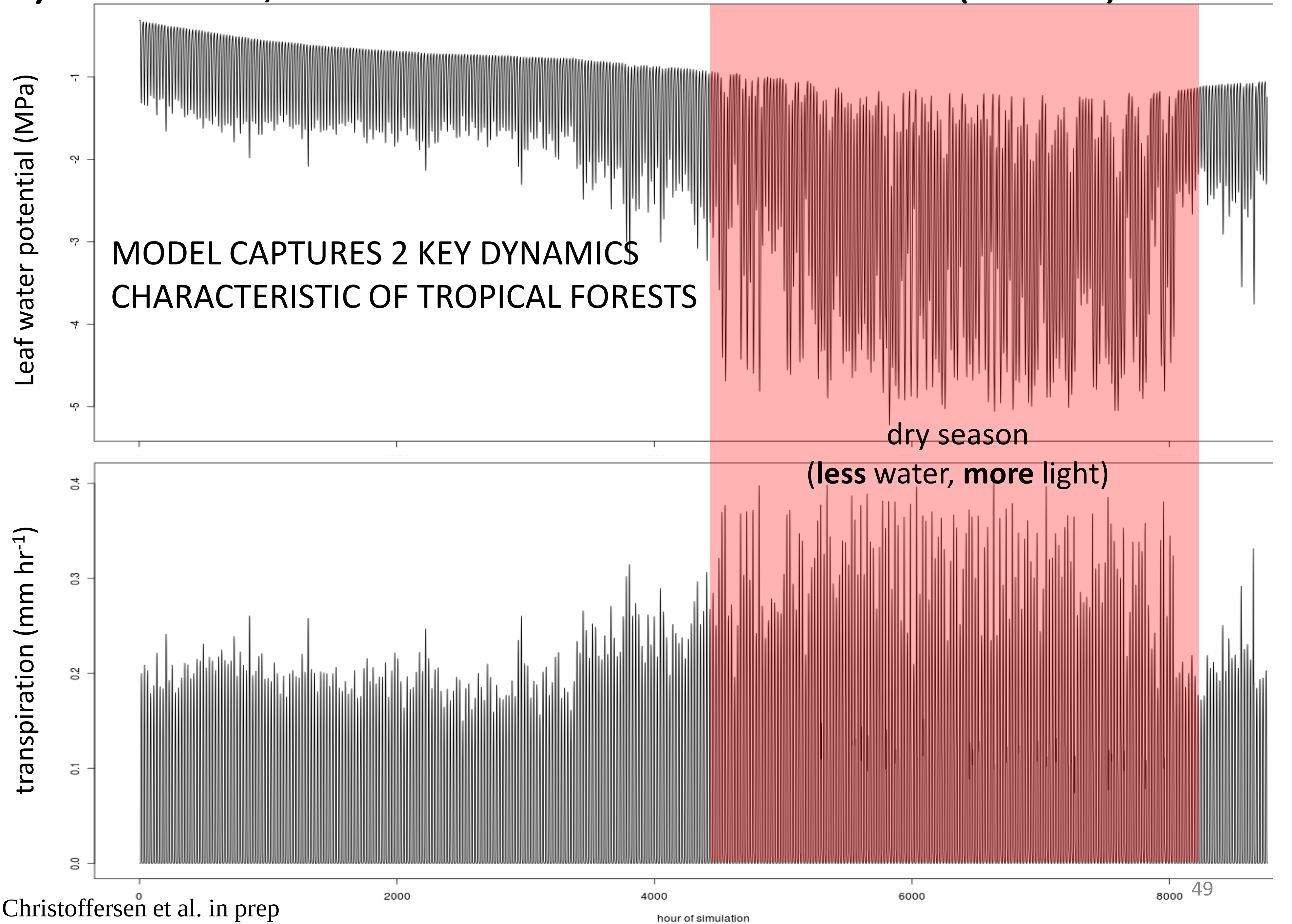
# 1-year simulation, 60cm DBH individual tree in Eastern Amazon (Caxiuana)

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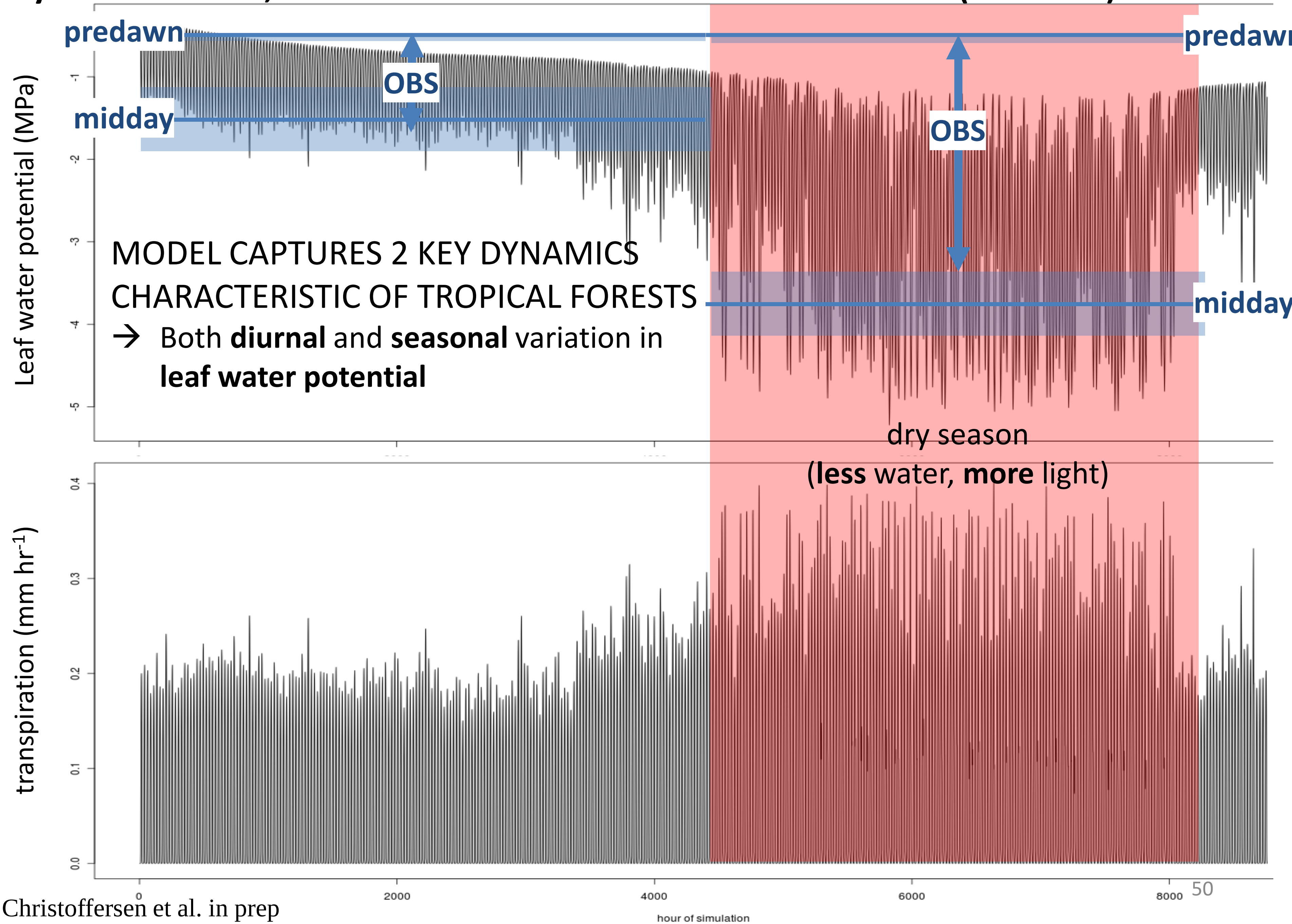
# 1-year simulation, 60cm DBH individual tree in Eastern Amazon (Caxiuana)

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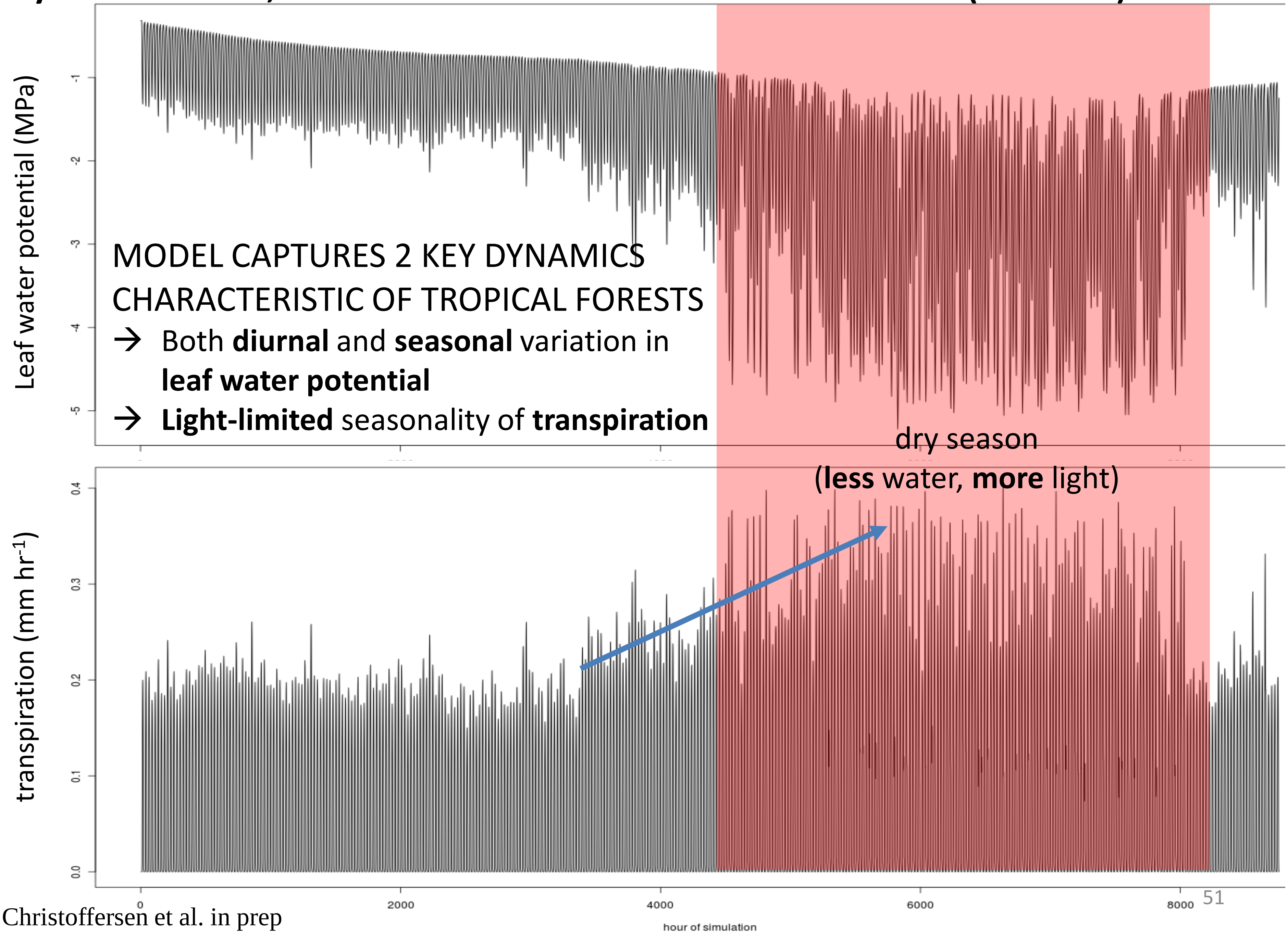
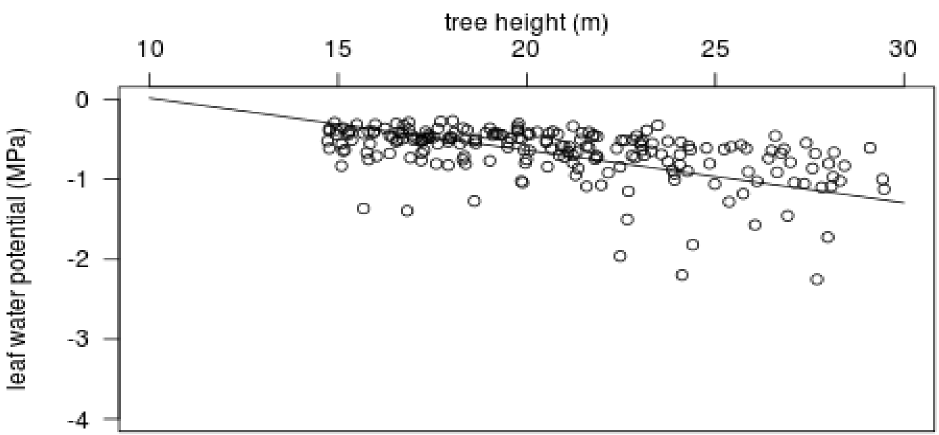
# 1-year simulation, 60cm DBH individual tree in Eastern Amazon (Caxiuana)

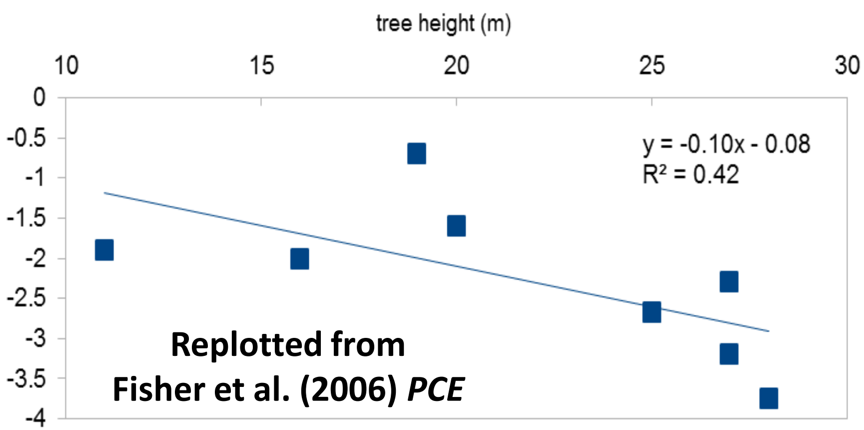


# Model captures height-related trends in leaf water status
## (1-yr simulation, Caxiuana)

**TFS model output**




**Data**

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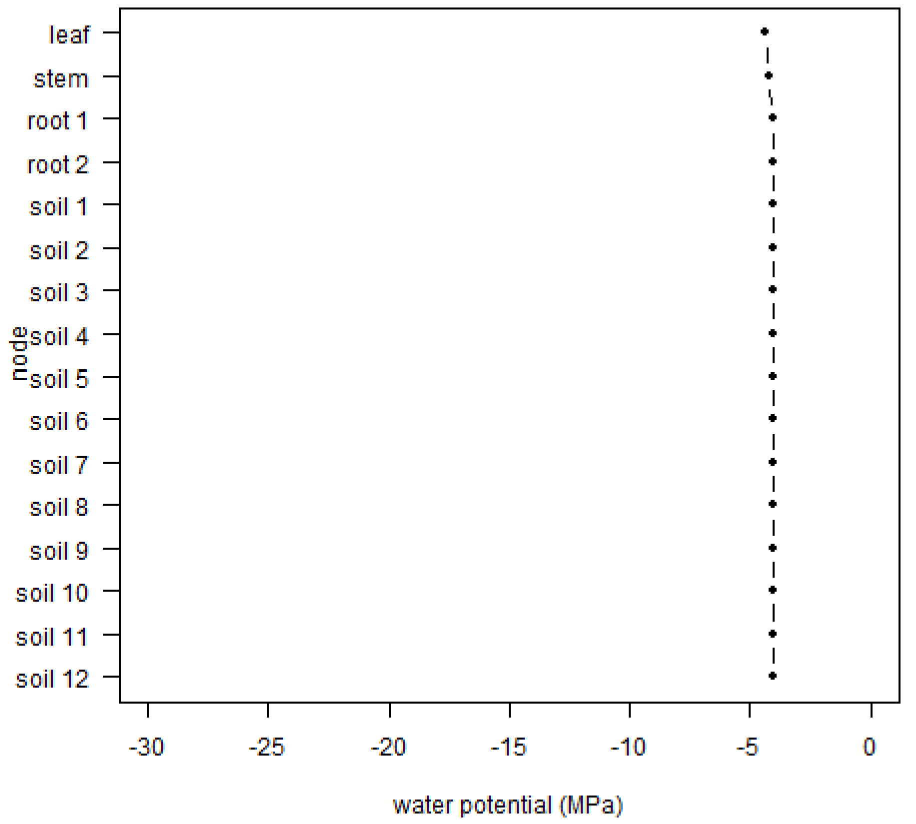
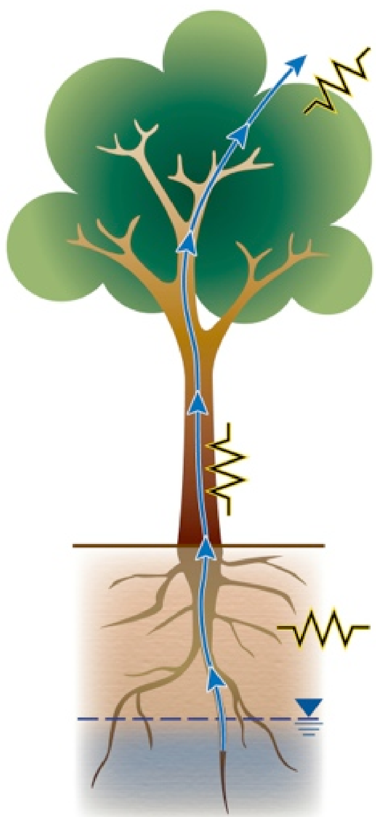
# Evolution of Hydraulic Failure under simulated drought



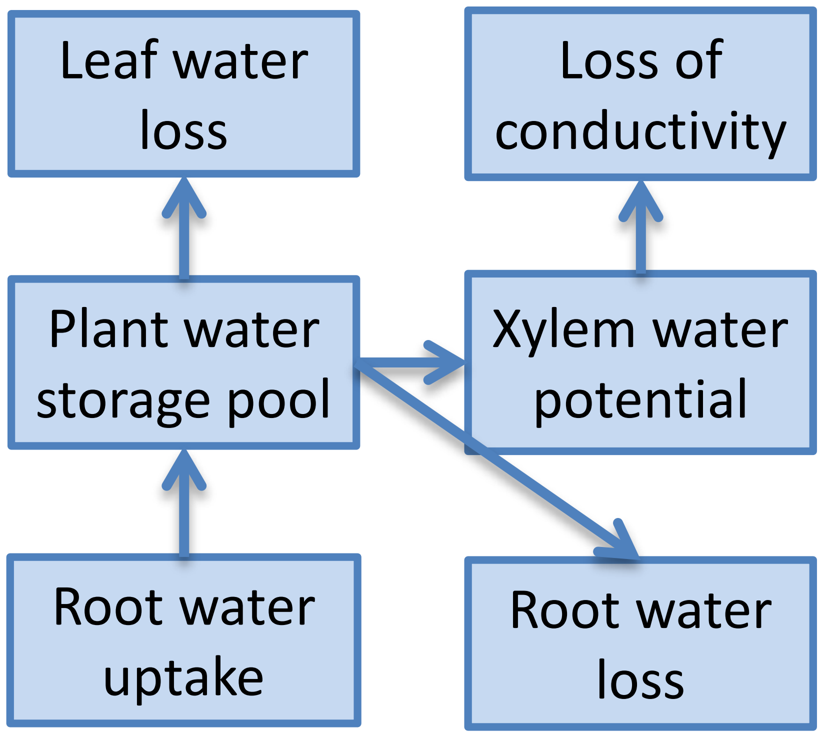

Christoffersen et al. in prep

# INITIAL ED(X) IMPLEMENTATION

# ED(X) new hydraulic failure model

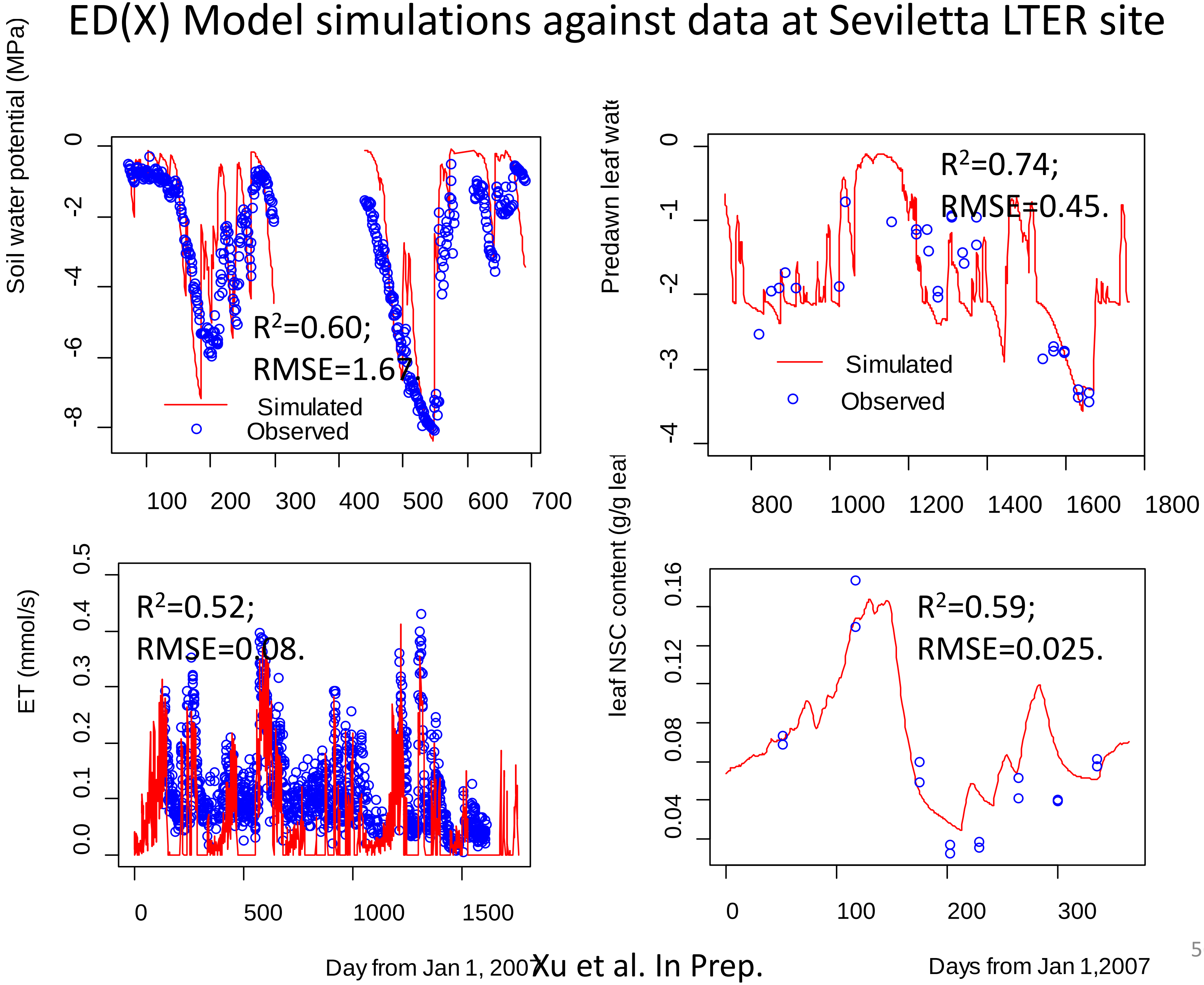


Hydraulic failure model



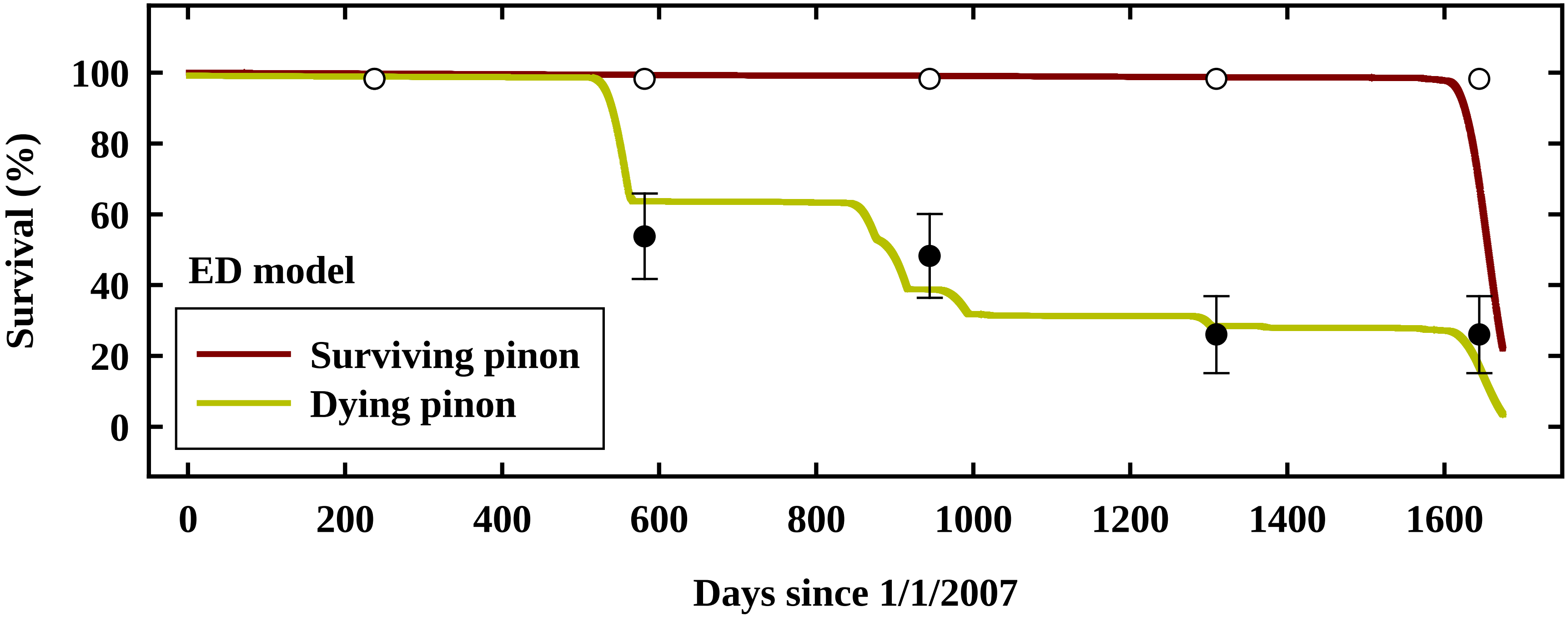

Xu et al 2013

# ED(X) Model simulations against data at Seviletta LTER site




Xu et al. In Prep.

# ED(X) mortality evaluations against data at Seviletta LTER site




McDowell et al. 2013

# Summary

- **Hydraulics Scheme**:
  - Dynamic plant conductance → hydraulic failure
  - Stomata: continuum of strategies (no $\psi_{leaf_{min}}$)
  - Efficient mass-based numerical solution
  - Stand-alone module for CLM(ED)

- **Traits**:
  - WD is useful predictor for hydraulic parameters

- **Hydraulic-Induced mortality**:
  - **Emergent** as catastrophic decline in $K_i$ **anywhere** in the continuum

- **Trait-based plant hydraulics modeling increases functional diversity in ESMs**