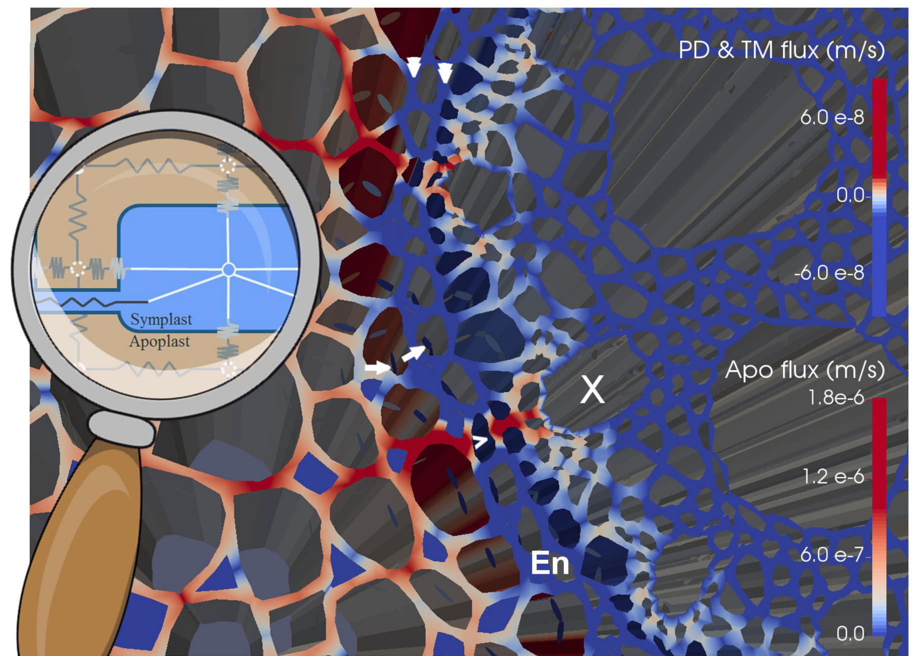
Emergent properties of plant hydraulic architecture: From root cells to cavitating stems and land surface models

V. Couvreur[1*], F. Meunier[1,2], G. Ledder[3], M. Sulis[4], S. Manzoni[5], G. Lobet[1,6], S. Russo[3], M. Javaux[1,6], J. Vanderborght[6], X. Draye[1]

1. UCLouvain, Belgium 2. Gent University, Belgium 3. University of Nebraska-Lincoln, USA 4. LIST, Luxembourg 5. University of Stockholm, Sweden 6. FZJuelich, Germany *Contact: valentin.couvreur@uclouvain.be

Context Hydrological processes in plants are multi-scale, involving sub-cellular elements such as **aquaporins** as well as long distance transport in **xylem** tissues vulnerable to cavitation in diverse root and shoot architectures. Their integration in dynamic vegetation models faces a major challenge: the avoidance of **over-complexification** while retaining the **essential features** of hydrological phenomena across scales.

1 MECHA: Simulating water flow in root transverse sections



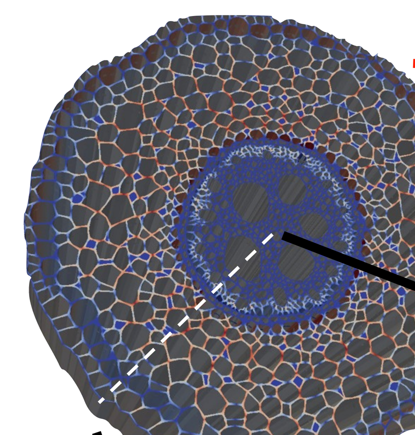
Color bars: Apoplastic fluxes on the transverse surface; Transmembrane and plasmodesmatal fluxes on longitudinal surfaces and ellipsoids in depth.

The model combines hydraulic and anatomical features at the cell-scale to simulate water flow across root tissues.

On the left, apoplastic fluxes converge toward passage cells (> symbol) of the endodermis (En) before reaching a xylem vessel (X).

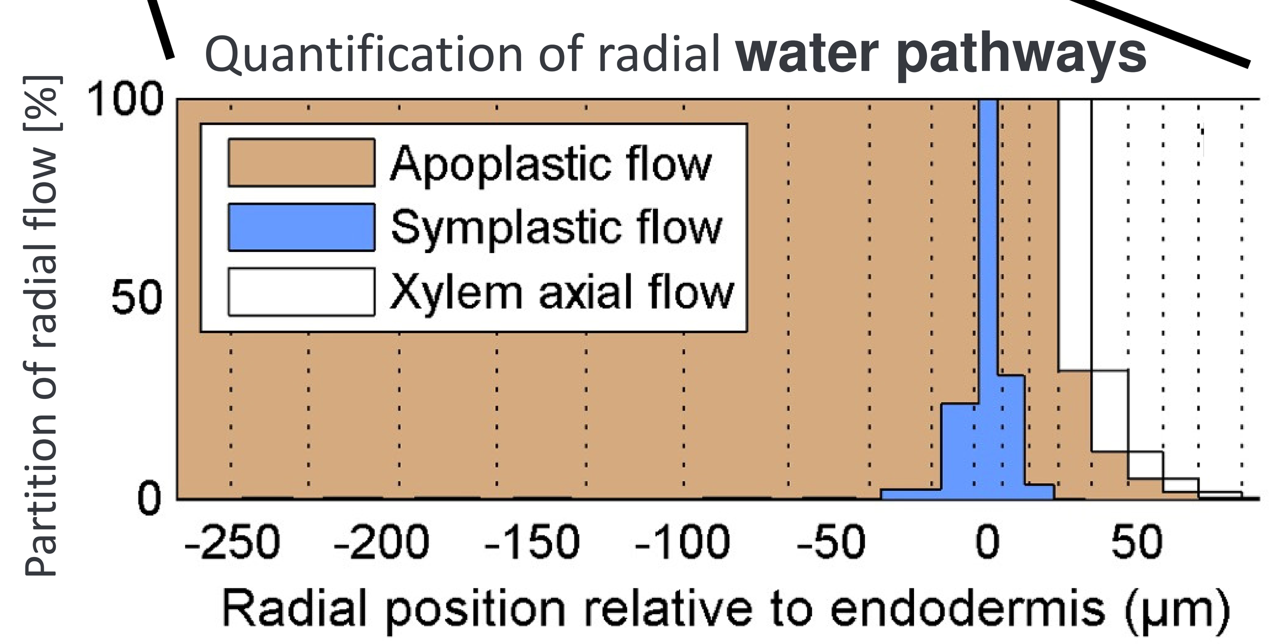
On the right, essential features (k_r and σ_r) estimated from the cell-scale are transferred to a higher scale model.

Try it online:
https://plantmodelling.shinyapps.io/mecha/

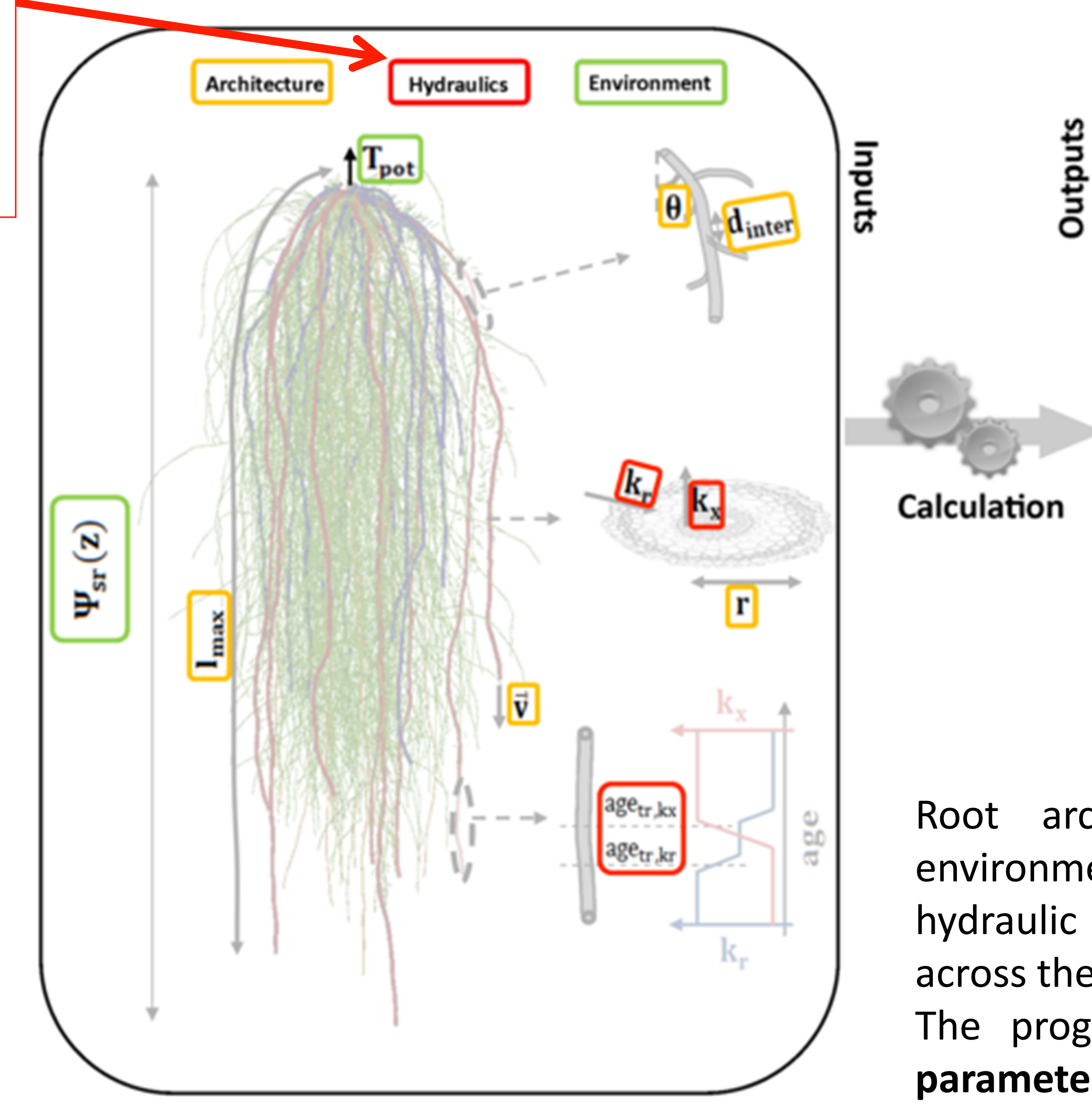


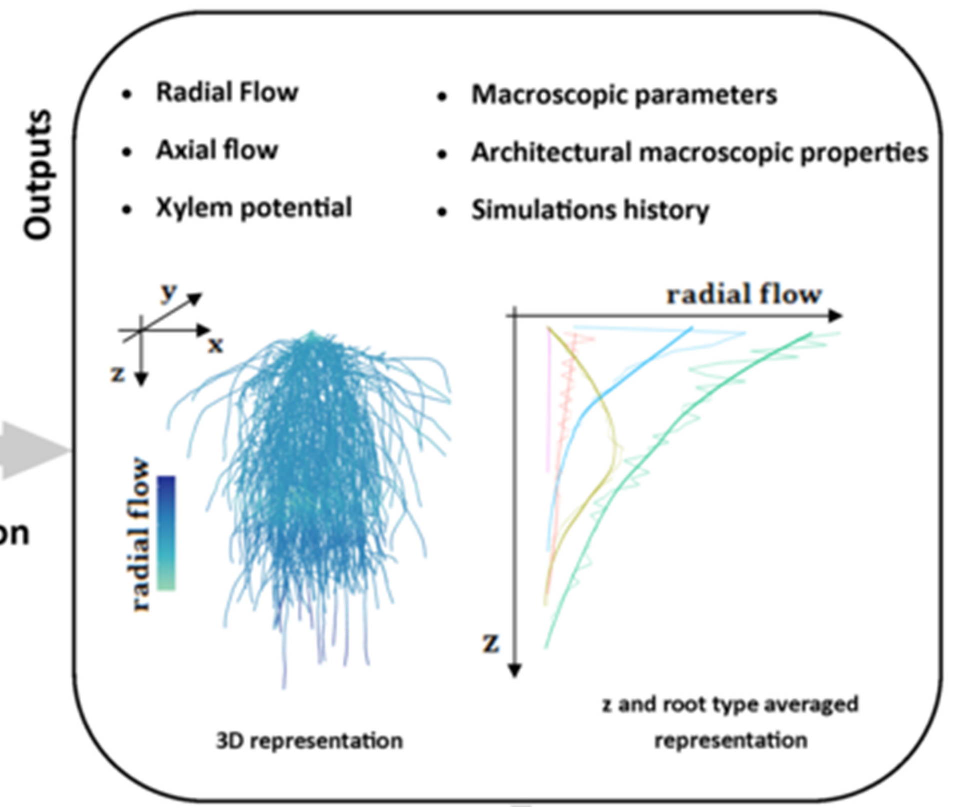
Root segment scale
hydraulic properties

k_r = root radial conductivity
σ_r = root reflection coefficient



2 MARSHAL: Simulating root growth and water flow in root hydraulic architectures





Root architectural (yellow), hydraulic (red), and environmental (green) inputs allow generating root hydraulic architectures and computing water flow across the root system.

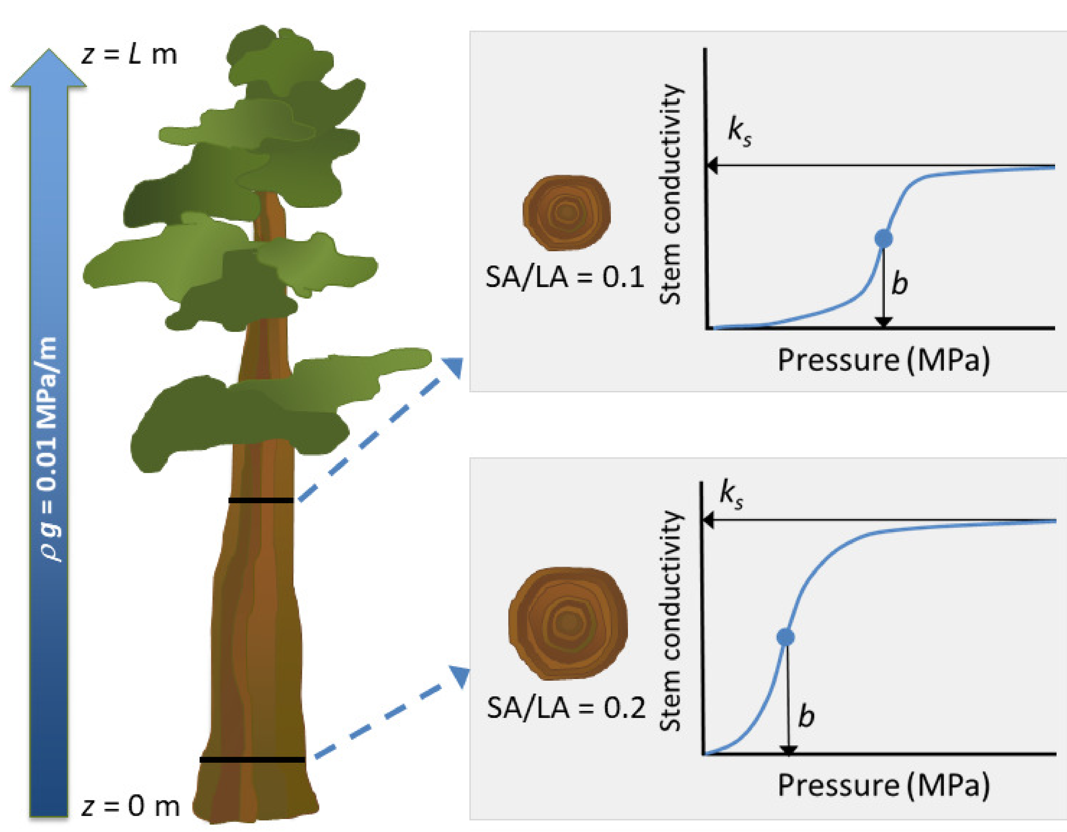
The program also calculates **macroscopic hydraulic parameters** ready for use in the Community Land Model (CLM).

Try it online:
https://plantmodelling.shinyapps.io/marshal/

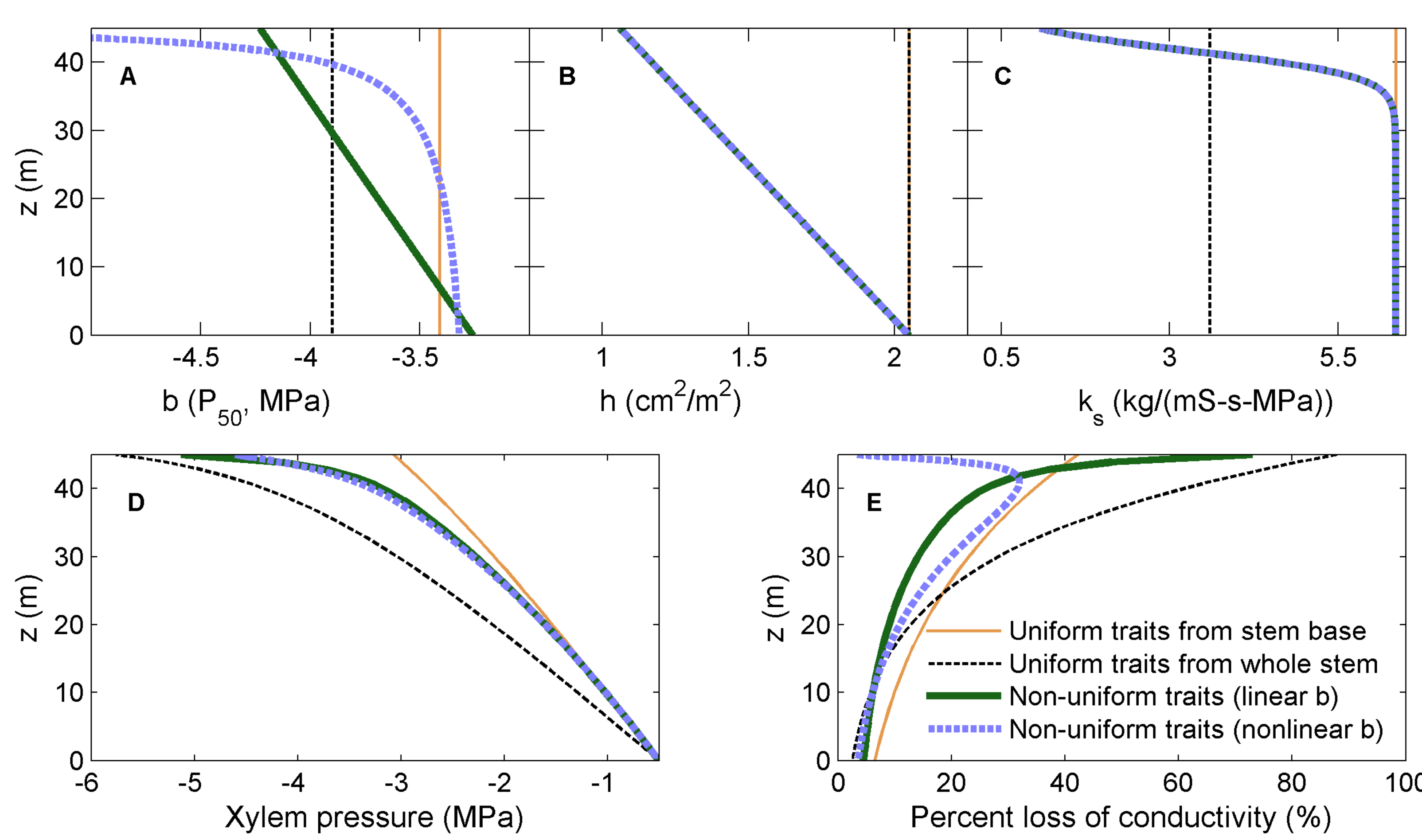
Plant scale **hydraulic properties**

K_{rs} = root system conductance
SSF = relative water uptake profile in uniformly wet soils

3 Simulating xylem cavitation along tall tree stems with a vertically explicit analytical hydraulic model



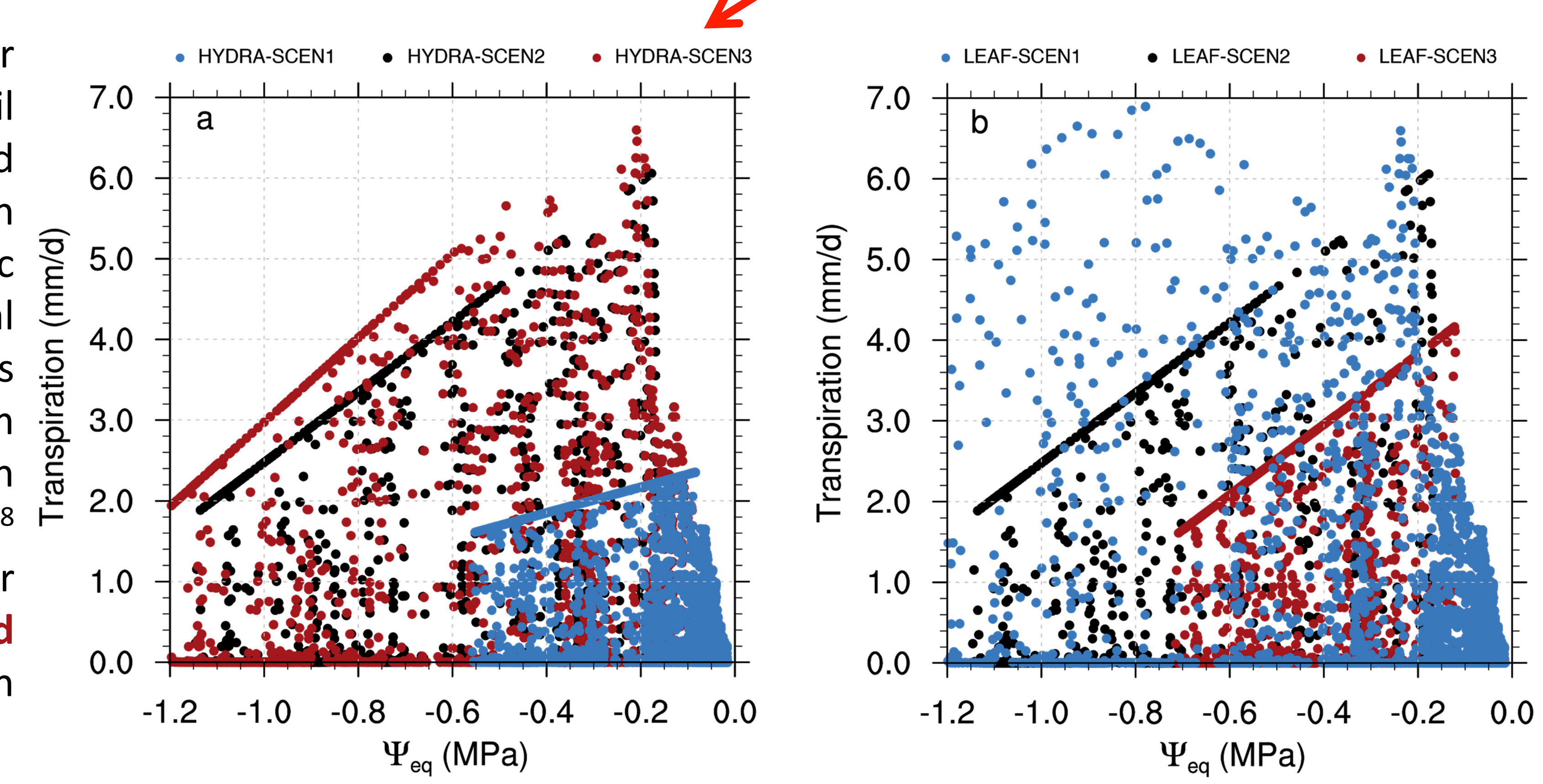
Stem geometry and hydraulic traits vary with height (z) in trees. The **Huber value** (*h*, ratio of sapwood area at z "SA" to leaf area above z "LA") is greater at the base of the tree; both the **xylem pressure at which 50% of stem conductivity is lost** (*b*) and the **stem-saturated hydraulic conductivity** (k_s) decrease with higher *z*. The gravitational potential of water increases by 0.01 MPa for every meter of tree height.



The innovation of the analytical model is to explicitly account for continuous variations of stem hydraulic properties (orange, **black**, **green** and purple curves in panels A, B, C) on the vertical profiles of xylem pressure (D) and percent loss of conductivity (E).
Some nonlinear traits may result in surprising complexity (see purple curve in panel E).

4 Simulating stomatal closure due to water deficit from first principles in Land Surface Models

The hydraulic parameter ***SSF*** ponders the soil water potential sensed by the plant ($\boldsymbol{\psi_{eq}}$). In leaves with isohydric control of stomatal aperture, $\boldsymbol{K_{rs}}$ corresponds to the slope of the stem water supply limitation vs $\boldsymbol{\psi_{eq}}$ ($\boldsymbol{K_{rs}}$ is $2 \cdot 10^{-8}$, $5 \cdot 10^{-8}$ and $6 \cdot 10^{-8}$ m s^{-1} MPa^{-1} for resp. blue, **black** and red plant functional types in panel a).



Plant response to water deficit was implemented in the leaf directly, based on empirical $\boldsymbol{\psi_{leaf*}}$ values (leaf water pressure at which stomata start to close). In panel b, $\boldsymbol{\psi_{leaf*}}$ varies from -2.5 (blue) to -1.1 MPa (red).

References:
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