Bridging the gap between empirical and mechanistic approaches in modeling plant transpiration under drought conditions

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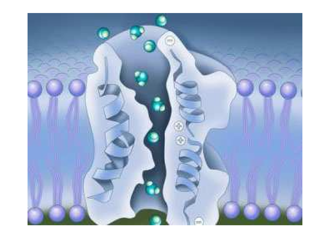
Introduction

In hydrological modeling, both empirical and mechanistic approaches have their own advantages, the former favoring simple relations between observed state variables, and the latter being rather process-based and allowing a deeper understanding of the system behavior. In cases both approaches match, a chance is given to interpret the simple empirical parameters in terms of bio-physical system properties.

In this study, we focus on the impact of two processes on isohydric plants transpiration:

- Regulation of aquaporin (AQP) activity in roots
- Formation of air gaps at soil-root interfaces

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Detailed modeling approach with R-SWMS

A mechanistic approach to modeling plant transpiration, and water uptake by roots, in a three-dimensional soil-plant system was developed by Javaux et al. (2008) in the modeling platform R-SWMS. R-SWMS iteratively solves **soil water flow** with Richards' equation and **water flow inside the root system** with Doussan model of root system hydraulics (Doussan et al., 1998).

Doussan model basically allows to consider:

- Complex root system **architectures** (see maize root system, Fig. 1a)
- Effect of **root type** (principal, lateral, …) on root hydraulic properties
- Effect of **root segment age** on root hydraulic properties (see Fig. 1b)
- Isohydric **regulation of stomata** under drought stress (i.e., stomata reduce plant transpiration in order to keep leaf water potential = H_{lim}).

So as to emphasize how local processes affect the system global behavior, simulations were run with **root radial conductivities** made dynamic, by using multiplying factors **sensitive to local soil water potential** (Fig. 1c):

- Increased AQP activity in dry conditions (blue)
- Decreased radial conductivity due to air gaps at soil root-interface (red)
- Both processes (yellow) or none of them (black).

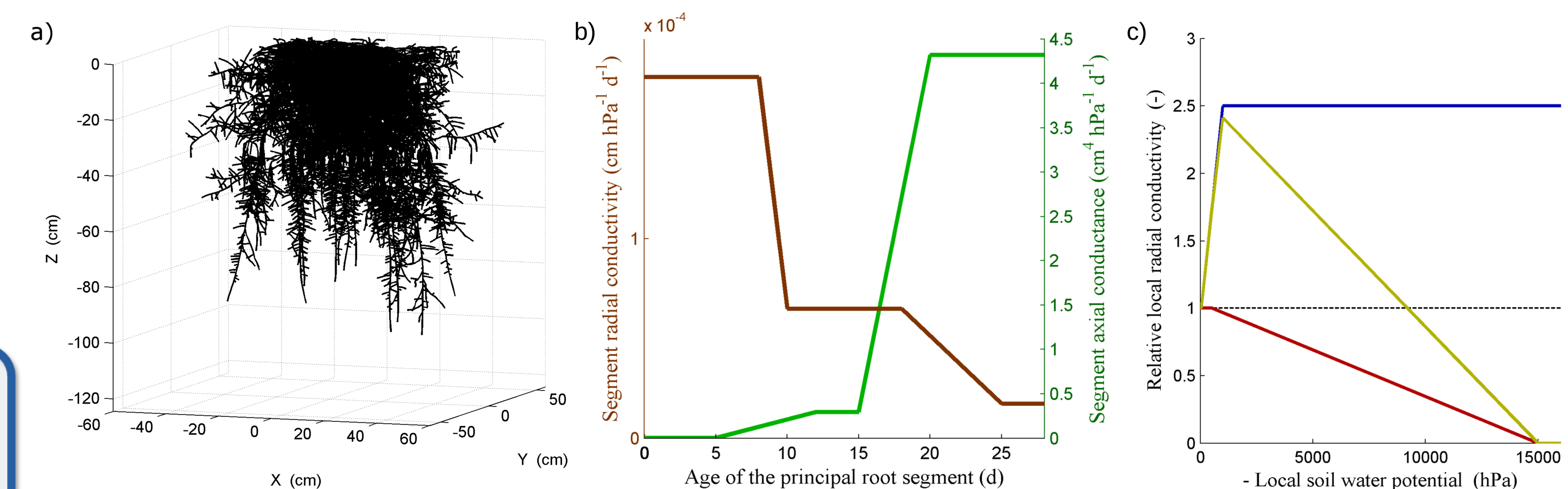

Fig. 1. Detailed root system properties description: (a) maize root system architecture generated with RootTyp (Pages et al., 2004), (b) principal roots axial and radial conductivities related to root segment age (from Doussan et al., 1998), and (c) multiplying factors of roots radial conductivities, related to local soil water potential. These factors account for an increased aquaporin activity (blue), air gaps at soil-root interfaces (red), and both processes (yellow).

Macroscopic approach and empirical observations

A simple macroscopic plant water stress model was recently developed by Couvreur et al. (2012). This model accurately reproduces the behavior of Doussan model of root system hydraulics, but its two parameters (***SSF*** and K_{rs}) are defined at the plant scale, rather than at the root segment scale. Equation 1 describes how isohydric plants transpiration evolves under drought stress ($H_{leaf} = H_{lim}$) with the macroscopic model:

$$T_{act} = K_{rs} . (\boldsymbol{SSF} \cdot \boldsymbol{H_s} - H_{lim}) \quad (1)$$

where T_{act} (L^3 T^{-1}) is the actual transpiration rate under stress, K_{rs} (L^3 P^{-1} T^{-1}) is the root system conductance, ***SSF*** (-) is the root system Standard Sink Fraction distribution, and $\boldsymbol{H_s}$ (P) is the soil water potential distribution.

Fig. 2 shows that the **shape of the macroscopic stress function** fits the generally observed empirical trend of transpiration rate reduction (T_{act} / T_{pot}) under water stress. This shape appears to be **determined by H_{lim} (intercept) and K_{rs} (slope)**, while the soil effective water potential is the scalar product of ***SSF*** by $\boldsymbol{H_s}$. As illustrated on figure 2c, using T_{act} as ordinate should lead to one single slope for the stress function, whatever the potential transpiration rate is.

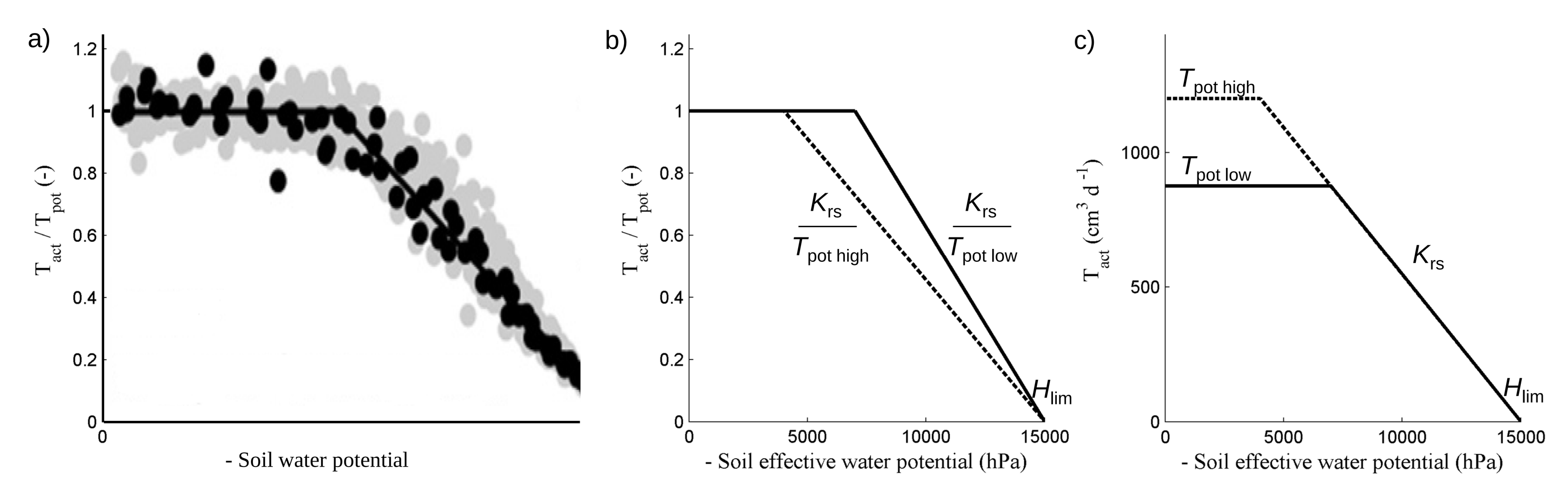

Fig. 2. (a) Generally observed empirical trend of transpiration rate reduction under drought stress (from Schoppach and Sadok, 2012). (b) Corresponding transpiration rate reduction predicted by the macroscopic model and values for the slope, with high (dashed line) and low (solid line) potential transpirations. (c) Same function with T_{act} used as ordinate.

Impact of local processes on plant global behavior under water stress

As expected, local processes impacted the system global behavior. Fig. 3 shows that the scenario with **air gaps and dynamic AQP activity** is the only one to present an **increase in both transpiration and soil water potential felt by the plant** as compared to the default scenario.

Fig. 4 illustrates the downward shift of the ***SSF*** due to air gaps at soil-root interfaces. This explains how **gaps allow the root system not to "feel" low soil water potentials** from the top of the profile.

Fig. 5 shows K_{rs} relation with soil effective water potential in the scenarios, and explains how a **high AQP activity allows to maintain high T_{act} under water stress.**

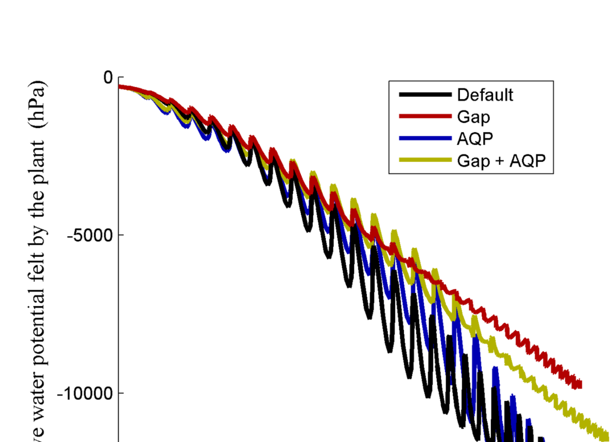

Fig. 3. Relation between cumulated transpiration and soil effective water potential in the scenarios.

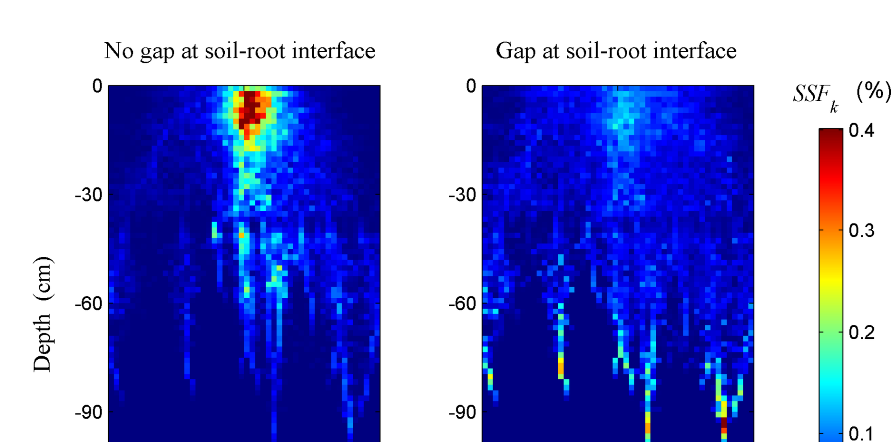

Fig. 4. Standard Sink Fraction distributions (SSF) at the end of the default (left) and gap (right) scenarios.

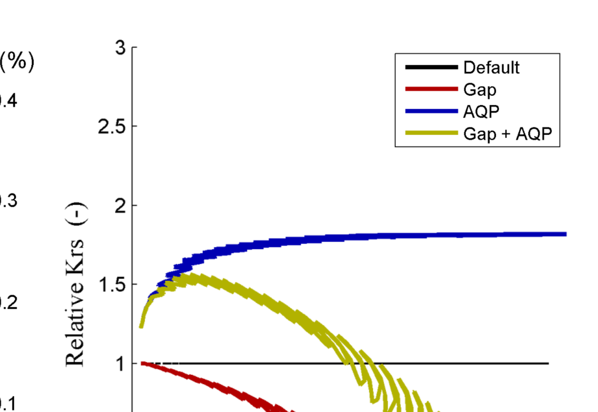

Fig. 5. Relation between K_{rs} and the soil effective water potential in the scenarios.

Conclusions and perspectives

A match was found between the typical empirically observed shape of plant transpiration rate reduction under water stress and a mechanistic water stress function for isohydric plants. This offers a chance to better understand transpiration regulation behavior and to link it to plant bio-physical properties. The results suggest the following deductions:

- Limiting leaf water potential (H_{lim}) and root system conductance (K_{rs}) would be major properties in plant transpiration regulation
- Air gaps' low hydraulic conductivity may help increase the soil effective water potential felt by plants ($\boldsymbol{SSF} \cdot \boldsymbol{H_s}$)
- Aquaporins may help plants maintain high transpiration by increasing root system conductance (K_{rs}).

However, a simple path that quantitatively leads from local to macroscopic dynamic properties (for instance, from Fig. 1c to Fig. 5) remains to be discovered, hopefully with astonishing outcomes like the quasi-linear water stress envelopes shown in Fig. 6.

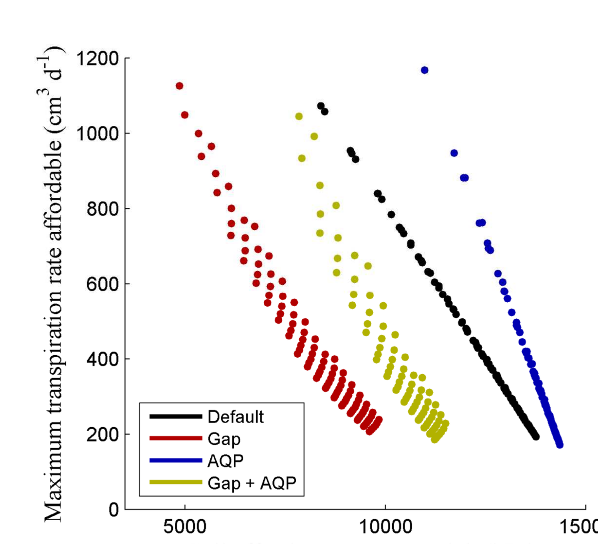

Fig. 6. Water stress envelopes.

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