A Mechanistic Root Water Uptake Model Including Root Resistance

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Introduction and objective

Modeling of root water uptake and its partitioning over depth is important to support hydrological, meteorological and crop growth modeling. Root water uptake distribution over depth as well as actual transpiration rate can be estimated from soil water matric flux potential, potential transpiration and root density data, following a method proposed by De Jong van Lier et al. (2008). However, in this method radial and axial hydraulic resistance are not considered, leading to overestimation of extraction rates, especially in wetter soil layers. We now present an extension of previous theory, including root resistances, and investigate its effect on model performance.

Theory - 1

We consider a single root of radius r_0 extracting water from a soil cylinder with radius r_m. The xylem has a cylindrical shape with radius r_x and is located in the exact center of the root (Figure 1). The root tissue ($r_x \le r \le r_0$) is considered to have a constant water content θ_{root}. The water content of the soil surrounding the root ($r_0 \le r \le r_m$) increases with distance from the root. At the root surface ($r = r_0$) a discontinuity in water content occurs (Figure 2).

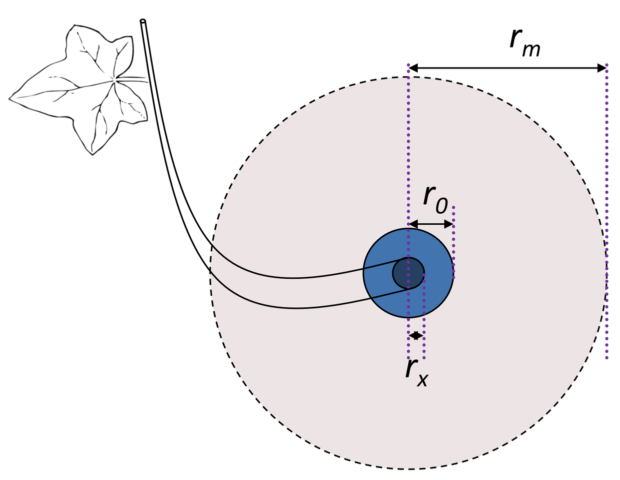

Figure 1 - Schematic representation of water extraction cone radius r_m, root radius r_0 and xylem radius r_x.

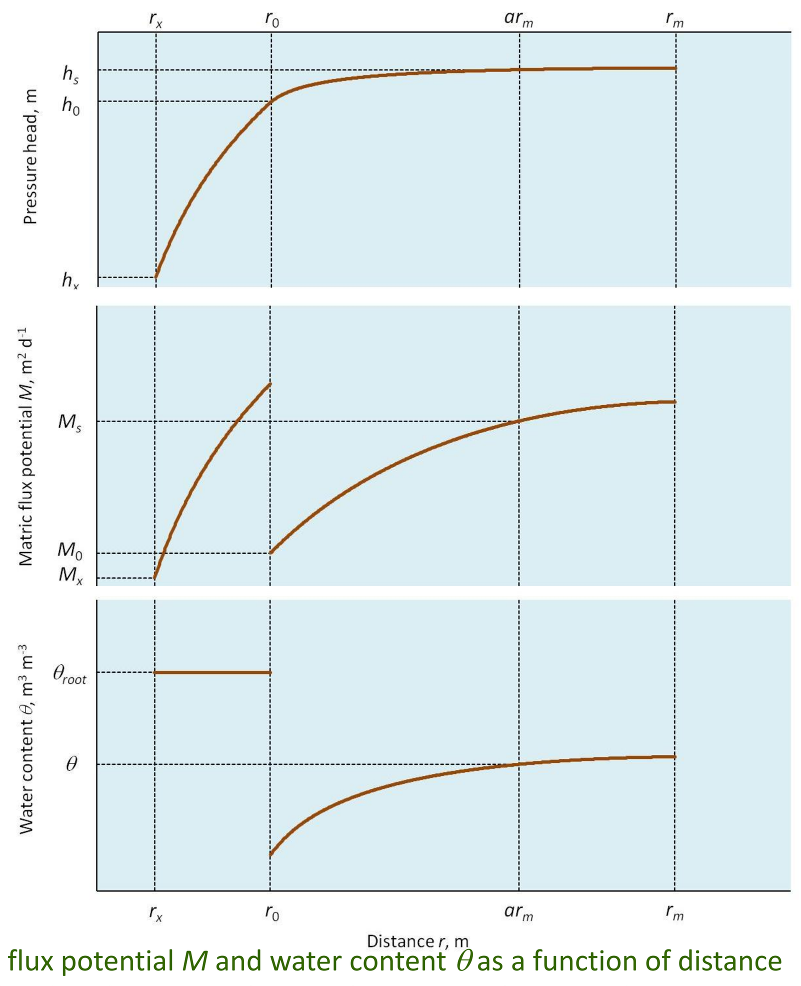

Figure 2 - Typical shapes of pressure head *h*, matric flux potential *M* and water content θ as a function of distance from axial center *r* in the rhizosphere and within the root under steady state conditions. Subscripts *x*, 0, *s* and *m* denote the outer xylem border, root surface, average soil and rhizosphere extension, respectively. ar_m is the distance where average conditions occur.

Theory - 2

1. Matric flux potential and Darcy equation: $M = \int_{h_w}^{h} K(h)dh \Rightarrow q = -\frac{dM}{dr}$
2. Matric flux potential in root: $M = K_{root}(h - h_w)$
3. Mass conservation in radial geometry: $\frac{\partial\theta}{\partial t} = -\frac{q}{r} - \frac{\partial q}{\partial r} = 0$
4. Combining 1. and 3.: $\frac{\partial M}{r\partial r} + \frac{\partial^2 M}{\partial r^2} = 0 \Rightarrow M = C_1 \ln r + C_2$
5. Applying boundary conditions: $M = M_x + \frac{S}{2} r_m^2 \ln\frac{r}{r_x}$
6. Applying 5. at $r = r_0$ and combining to 2.: $h_0 = h_x + \left. S r_m^2 \ln\frac{r_0}{r_x} \middle/ 2K_{root} \right.$
7. Xylem and leaf water potential relate like: $h_x = h_l + \frac{T_a}{L_l}$
8. Combining 6. and 7.: $h_0 = h_l + \frac{T_a}{L_l} + \left. S r_m^2 \ln\frac{r_0}{r_x} \middle/ 2K_{root} \right.$
9. De Jong van Lier et al. (2008) showed that: $S = \frac{4(M_s - M_0)}{r_0^2 - a^2 r_m^2 + 2(r_m^2 + r_0^2)\ln\frac{a r_m}{r_0}} = \rho(M_s - M_0)$
10. Substituting 9. in 8. yields

$$h_0 + \varphi M_0 = h_l + \varphi M_s + \frac{T_a}{L_l};\ \varphi = \frac{\rho r_m^2 \ln\frac{r_0}{r_x}}{2K_{root}}$$

Interpretation of 10.: For a given soil-root system with known values of r_x, r_0, r_m, K_{root} and a, fixing a value of water potential in the leaves (h_l) and matric flux potential in the soil (M_s) allows calculating $h_0 + \varphi M_0$. *M* being a function of *h*, h_0 and M_0 for the given combination of parameters can be found. On its turn, solving for M_0 allows calculation of *S* by applying 9.

Results and discussion

Application of 9. requires an iterative procedure which was included in the SWAP ecohydrological model. Scenario´s of two field experiments (both in Brazil, one with Common Bean under very dry conditions, the other one with Soybean under wet conditions) were simulated with SWAP using three reduction functions: the function by Feddes et al. (1978 - **FRF**) with h_{3h} = -7.5 m, h_{3l} = -20 m and h_4 = -150 m, the function proposed by De Jong van Lier et al. (2008 - **JRF**) with h_w = -150 m, and the newly proposed (**JRF-r**) reduction function including radial resistance, using $K_{root} = 3.5\cdot10^{-6}$ cm d^{-1}, $L_l = 1.0\cdot10^{-4}$ d^{-1} and $h_{l,min}$ = -200 m. Figure 3 shows simulated extraction rates as a function of time and depth, as well as simulated relative transpiration. Table 1 shows statistical indices.

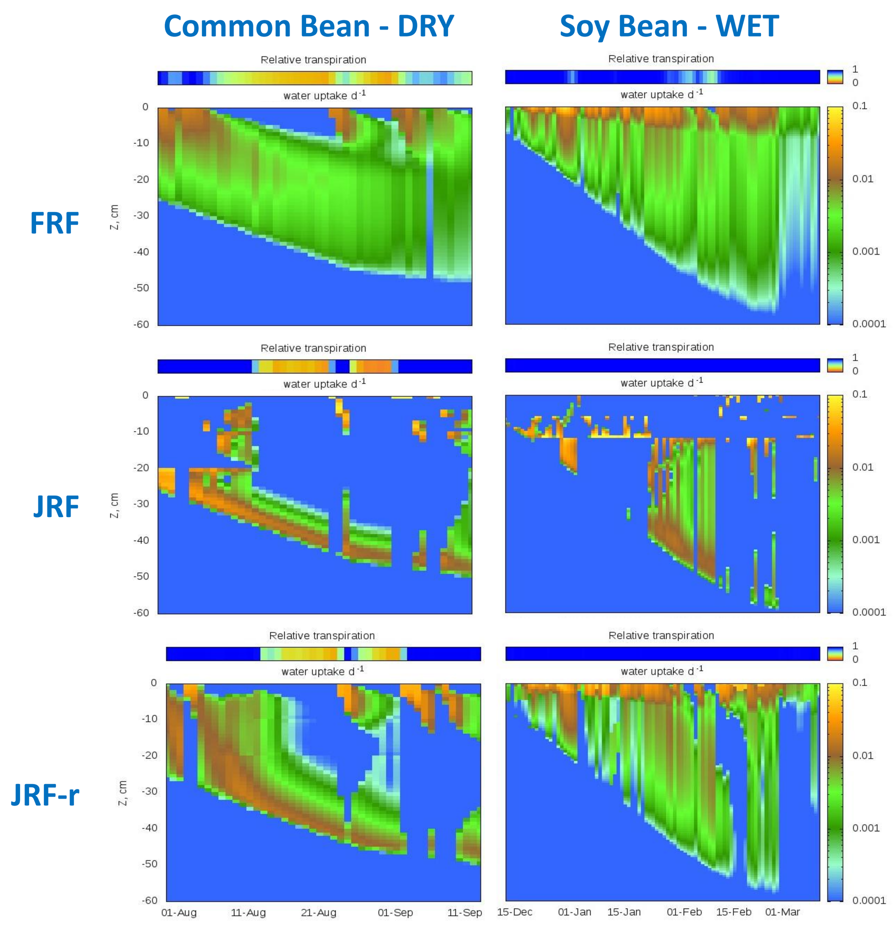

Figure 3 - Simulated water extraction rates and relative transpiration as a function of time and depth for two field experiments (Common Bean under very dry conditions; Soy Bean under wet conditions), obtained with the SWAP model in combination with three reduction functions.

		RMSE	MAE	E	R^2	d
Bean – Dry conditions						
5 cm	*FRF*	0.04	0.12	0.34	0.606	0.727
	JRF	0.04	0.12	0.36	0.616	0.740
	JRF-r	0.04	0.12	0.32	0.603	0.740
15 cm	*FRF*	0.02	0.05	0.71	0.738	0.916
	JRF	0.02	0.05	0.62	0.722	0.905
	JRF-r	0.02	0.06	0.53	0.713	0.891
30 cm	*FRF*	0.02	0.04	0.64	0.879	0.854
	JRF	0.03	0.04	0.32	0.808	0.840
	JRF-r	0.02	0.04	0.39	0.853	0.860
Soybean – Wet conditions						
15 cm	*FRF*	0.04	0.07	-1.58	0.391	0.656
	JRF	0.03	0.07	-0.49	0.351	0.704
	JRF-r	0.04	0.08	-1.90	0.342	0.627
30 cm	*FRF*	0.03	0.07	0.27	0.446	0.802
	JRF	0.02	0.07	0.37	0.470	0.810
	JRF-r	0.03	0.08	0.06	0.439	0.780

Table 1 - Statistical indices of comparison (RMSE and MAE in m^3 m^{-3}, Coefficient of Efficiency *E*, R^2 and Willmott´s coefficient of agreement *d*) between field observations and SWAP simulations of volumetric water content for the three transpiration reduction functions.

Extraction patterns simulated by the FRF are smooth; no compensation of water uptake is simulated in this model, therefore transpiration reduction remains even after a rainfall event in dry conditions, like on 25-Aug. Contrarily, JRF and JRF-r predict a total relief of water stress shortly after this event. The JRF shows a very patchy extraction pattern, occasionally with very high extraction rates from only a thin layer of a few centimeters, as well as abrupt changes at layer borders (e.g. at 10 cm depth), especially in the wet experiment. This is counterintuitive and is greatly improved in the JRF-r. The extraction pattern simulated with JRF-r resembles FRF, but implicitly includes compensation. Differences between FRF and JRF-r may be reduced by proper calibration of both functions.

Statistical performance of all three models is very similar (Table 1). Parameter calibration will be a priority for further research.

Conclusions

An analytical expression for root water extraction including soil and plant resistance was developed. It is capable of quantifying potentials along the soil-root-leaf pathway. Implementation in a hydrological model shows extraction patterns to be more consistent than for the model without plant resistance.

Cited literature

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