Optimizing root system hydraulic architectures for water uptake

Félicien Meunier[1*], Valentin Couvreur[2], Xavier Draye[3], Jan Vanderborght[4], Mathieu Javaux[1,4] (*felicien.meunier@uclouvain.be)

1. Earth and Life Institute – Environment , Université catholique de Louvain, Belgium
2. Department of Land, Air and Water Resources, UC Davis, USA
3. Earth and Life Institute – Agronomy, Université catholique de Louvain, Belgium
4. Forschungszentrum Jülich GmbH, Agrosphere (IBG-3), Germany

Introduction

Water stress is among the dominant yield limiting factors in global crop production. A fundamental understanding of root water uptake (RWU) is therefore needed to enable breeding of drought resistant plants and to improve irrigation strategies. In this context physical models of root system Hydraulic Architecture (HA) have been recently developed to simulate the RWU. We propose here a new modelling strategy dedicated to the optimization of HA.

Analytical macroscopic parameters calculation

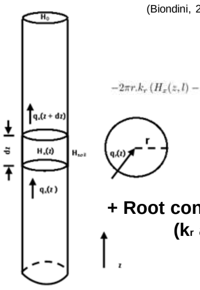
The water flow problem inside a single root leads to equation [1] which can be solved if specific boundary conditions (soil and collar potentials) are given as well as the hydraulic properties of the considered root.

The xylem potential, the radial and axial root flows, solutions of the water balance problem, are equations [2] under simplifying assumptions of constant radial and axial conductivities and soil and collar potentials.

Thanks to [2] we finally have access to the macroscopic parameters of the single root (equations [3]) that can be used in any RWU models. Approximations of these parameters are useful in hydraulic experiments

Water flow in a root

(Biondini, 2008)



$$-2\pi r.k_r\left(H_x(z,l)-H_{soil}\right) = -k_x\frac{\partial^2 H_x(z,l)}{\partial z^2} \quad [1]$$

+ Root conductivity functions (k_r and k_x)

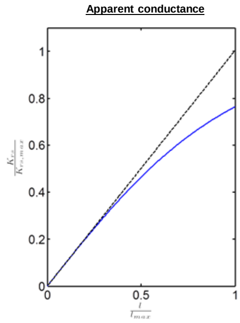
$$H_x(z,l) = H_{soil} + \frac{H_0 - H_{soil}}{exp(\kappa)+exp(-\kappa)}.\left[exp\left(\frac{\kappa}{l}z\right)+exp\left(-\frac{\kappa}{l}z\right)\right]$$

$$q_x(z,l) = -k_x\left(\frac{\kappa}{l}\right).\left(\frac{H_0 - H_{soil}}{exp(\kappa)+exp(-\kappa)}\right).\left[exp\left(\frac{\kappa}{l}z\right)-exp\left(-\frac{\kappa}{l}z\right)\right] \quad [2]$$

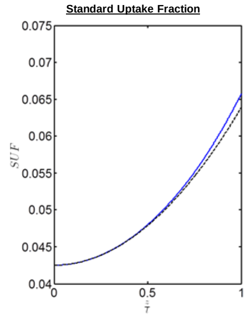
$$q_r(z,l) = -k_x\left(\frac{\kappa}{l}\right)^2\left(\frac{H_0 - H_{soil}}{exp(\kappa)+exp(-\kappa)}\right).\left[exp\left(\frac{\kappa}{l}z\right)+exp\left(-\frac{\kappa}{l}z\right)\right]$$

Macroscopic parameters

Apparent conductance



Standard Uptake Fraction

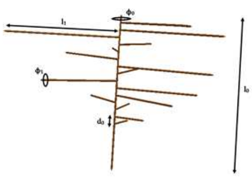


$$K_{rs}(l) \triangleq \frac{q_x(z=0,l)}{H_0-H_{soil}} = \frac{k_x.\kappa}{l}tanh(\kappa) \simeq 2\pi r k_r l \qquad SUF(z,l) \triangleq \frac{q_r(z,l)}{K_{rs}\left(H_0-H_{soil}\right)} = \frac{\kappa}{l}\frac{cosh\left(\frac{\kappa}{l}z\right)}{sinh(\kappa)} \simeq \frac{\kappa}{l}\frac{1}{sinh(\kappa)}.\left(1+\frac{\left(\frac{\kappa}{l}z\right)^2}{2!}\right) \quad [3]$$

Complex root hydraulic architecture

Root growth model

(Pagès et al., 2004)



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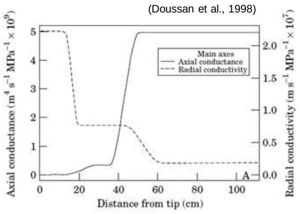
Root hydraulic conductivities

(Doussan et al., 1998)



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Macroscopic parameters calculation

(Couvreur et al., 2012)

Solution: $\boldsymbol{H_x} = \boldsymbol{c^{-1}}\left(\boldsymbol{diag}(-\boldsymbol{k_r})\boldsymbol{H_{soil}} - \begin{bmatrix} k_{x1}H_0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}\right)$

$\boldsymbol{q_r} = \boldsymbol{diag}(\boldsymbol{k_r}).(\boldsymbol{H_{soil}} - \boldsymbol{H_x})$

$$K_{rs} = \frac{\sum \boldsymbol{q_r}}{|H_0 - H_{soil}|} \qquad \boldsymbol{SUF} = \frac{\boldsymbol{q_r}}{\sum \boldsymbol{q_r}} \quad [4]$$

If either the root architecture or the hydraulic properties are complexer, analytical solution can not be found anymore. We then use numerical solutions of water flow to obtain the macroscopic parameters of growing root systems [4].

Optimization procedure

Both models can be submitted to optimization under volume constraint and in a given range of root growth parameters, mathematically:

Objective function examples:

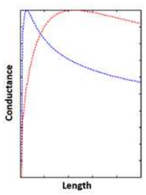
$$max(K_{rs}) \quad or \quad max(V_{soil})\ explored\ by\ \boldsymbol{SUF}$$

Subject to:

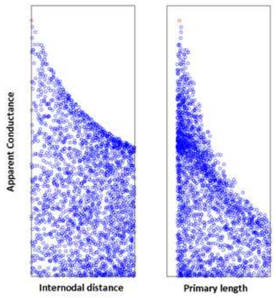
$$V_{root} = V_0$$

$$\boldsymbol{RG_{param,D}} \le \boldsymbol{RG_{param}} \le \boldsymbol{RG_{param,U}}$$

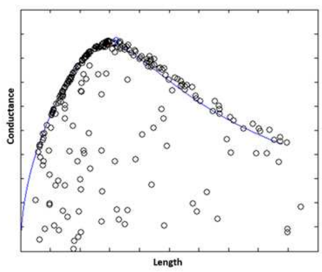
Results



Optimal root parameters are then found either analytically (single root problem for two different hydraulic properties, left) or numerically (complex root architecture, right). The sensitivity of the objective function to the root parameters are obtained at the same time.

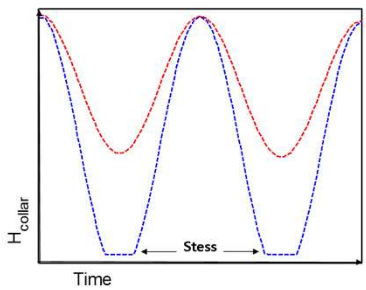


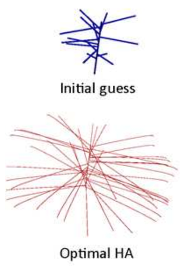
Model validation



The optimization algorithm is capable of retrieving the best parameters predicted by the analytical solution (left).

The optimization procedure leads to the best hydraulic architecture for a given volume. Performance can be effectively compared thanks to a 3D-detailled RWU model (RSWMS (right), javaux et al., 2008)





Conclusion

A new method has been developed to select the best HA in a range of growth parameters and for a specific hydraulic behaviour. Such a model can now be used to respond scientific questions such as “*What is the best sowing density of a given phenotype?*” or *“What is the importance of root angle or growth velocity rate for water uptake ?”*

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