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Using thermodynamics to assess biotic and abiotic impediments to root water uptake

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Root water uptake has been the subject of extensive research, dealing with understanding the processes limiting transpiration and understanding strategies of plants to avoid water stress. Many of those studies use models of water flow from the soil through the plant into the atmosphere to learn about biotic and abiotic factors affecting plant water relations. One important question in this context is to identify those processes that are most limiting to water transport, and specifically whether these processes lie within the plant or the soil?

Here, we propose to use a thermodynamic formulation of root water uptake to answer this question. The method allows us to separate the energy exported at the root collar into a sum of energy fluxes related to all processes along the flow path, notably including the effect of increasing water retention in drier soils. Evaluation of the several contributions allows us to identify and rank the processes by how much these impede water flow from the soil to the atmosphere.

The application of this approach to a complex 3-dimensional root water uptake model reveals insights on the role of root versus soil resistances to limit water flow. We investigate the efficiency of root water uptake in an ensemble of root systems with varying root hydraulic properties. While root morphology is kept the same, root radial and axial resistances are artificially varied. Starting with entirely young systems (uptake roots, high radial, low axial conductance) we increasingly add older roots (transport roots, high axial, low radial conductance) to improve transport within root systems. This yields a range of root hydraulic architectures, where the extremes are limited either by radial uptake capacity or low capacity to transport water along the root system. We model root water uptake in this range of root systems with a 3-dimensional root water uptake model in two different soils, applying constant flux boundary conditions in a dry down experiment and evaluate energy fluxes afterwards.

The results show that a minimum of energy is exported in mixed root systems, but a wide range of root systems act near the optimum. A great loss of efficiency only occurs in the extreme cases (only young or only old roots). In all systems near the optimum root water uptake is impeded equally by abiotic and biotic factors in moist conditions, whereas abiotic factors become the limiting factor in dry conditions. The abiotic factors depend on the soil type and are either due to the water retention function or water flow towards individual roots. Small changes in the distribution of root resistance shift the impediments from radial to axial flow path within the root, but without much affecting overall energy export. This suggests that abiotic factors are a dominant control for efficient root water uptake, while morphology only has a comparatively smaller effect, as long as the root system contains a minimum mixture of uptake and transport roots.