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How to scale root water uptake from root scale to stands and beyond – a theoretical framework, practical lessons, and next steps

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Estimating plant uptake of soil water has been a persistent problem in process-based earth system models (ESMs). Initially ignored altogether, plant access to soil water was long modelled with heuristic approaches at large scales. These formulations are currently being replaced as ESMs begin to incorporate more detailed plant hydraulics schemes based on the soil-plant-atmosphere continuum concept. While the new schemes greatly improve mechanistic description of above-ground plant hydraulics, they have given rise to various issues belowground, from excessive hydraulic redistribution to numerical instability. As detailed 3D descriptions of root systems and water flow equations on the soil-root domain have been established, the key challenge is how to scale them up to relevant scales, reducing computational cost to a trivial level without loss of accuracy.

Here, we set out a mathematical framework that incorporates recent advances in this area and allows us to relate them to each other. Comparing and contrasting different models, formulated in a novel matrix form of the water flow problem in the root system, allows us to make inferences about their suitability for use in upscaling. We are able to show how to avoid discretization error in the upscaled root scheme, as well as which upscaling method offers full generality, and which yields the computationally simplest forms. These theoretical results are fully supported by numerical simulations of fully explicit 3D root systems and their upscaled versions. Improved performance of the upscaled models is also demonstrated in an application to field data from the Wind River Crane flux tower site (reduced model bias, root mean squared error, and increased robustness of fitted parameters).

Root water uptake equations can now be scaled up without discretization error for arbitrary root systems. The chief remaining source of error is soil moisture heterogeneity within discretized soil elements where it is assumed uniform by any given model (e.g. within each vertical layer). The main task for future work thus becomes to achieve a correspondingly accurate description for soil moisture heterogeneity. Some of the upscaling approaches compared here offer hints at potential next steps in this direction.