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Predicting plant water limitation in heterogeneously drying soils: the upscaling approach to improving soil-plant hydrodynamics in ESMs

Martin Bouda[1], Jan Vandergborght[2], Valentin Couvreur[3], and Mathieu Javaux[2,3]
[1]Institute of Botany, Czech Academy of Science, Pruhonice, Czechia
[2]IBG-3 Agrosphere, Forschungszentrum Jülich, Jülich, Germany
[3]Earth and Life Institute, Université Catholique de Louvain, Louvain-la-neuve

Limitation of photosynthesis by soil moisture variability is increasingly understood to be a central factor in the land carbon balance. Soil moisture dynamics are thought to be responsible for the bulk of interannual variability in the land carbon sink as well as the uncertainty in predicting it.

A key challenge in understanding this process is the mismatch between the spatial scales of cause and effect. Sharp and localised gradients in soil moisture availability can develop during drought, presenting a difficulty both for plants and researchers. Soil moisture heterogeneity triggers nonlinearities in flow in both the soil and plant, whose effects are not captured by current earth system models (ESM).

Most descriptions of soil moisture limitation of plants at earth system scales rely on a heuristic macro-scale 'stress factor' formulation that fails to adequately reflect current understanding of the inherently small-scale process. Recently, some models have adopted a linearised formulation of bulk flows in response to water potential gradients. While this step theoretically improves mechanistic representation of the process, increased prediction errors persist when vertical differences in soil moisture emerge while horizontal heterogeneity is commonly not represented at all.

This presentation introduces the upscaling approach to addressing this knowledge gap, which seeks new formulations of soil-plant hydrodynamics that bridge the scales of cause and effect. This approach relies on describing soil-plant hydrodynamics from first principles at small scale and mathematically scaling up the resulting formulations: deriving simple bulk scale forms while introducing as few approximations or errors as possible. Recent advances in this line of research include a fully general algorithm for upscaling the nonlinear equations describing flows in the root system without introducing discretisation error or increasing computational cost of finding solutions. Ongoing work aims to explore opportunities for addressing nonlinearities in the soil that arise from conceptual advances achieved in upscaling the plant flows. Applying the outputs of this promising theoretical approach in earth system models will require future empirical work to constrain the parameters of the new models at multiple scales.