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Diurnal and inter-day hysteresis of species-specific stomatal conductance from sap-flow measurements illustrates hydraulic-stress responses strategies of trees

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Modeling of plant hydraulics is at the forefront of development in vegetation and land-surface models. Numerical tools that consider water flow within the conductive system of plants, and particularly trees, have been developed and used in studies of hydraulic strategy and consequences of hydraulic behavior for drought tolerance. Several established land-surface models such as ED2, CLM, and E3SM have recently developed “hydro” versions and are ready to extrapolate the consequences of including tree hydraulic behaviors into large scale and global simulations. At the core of any plant hydrodynamic model is the assumption that stomatal conductance is dependent on xylem water potential. Further, “plant hydro” models assume that the effect of soil moisture on stomatal conductance is not direct but cascades through depletion of xylem water content in dry soil conditions.

We use observations of sap flow, soil moisture, and evapotranspiration at a mixed forest in the University of Michigan Biological Station (UMBS) at the footprint of the US-UMd flux tower to characterize the onset and advancement of hydraulic stress and post-stress recovery. We define stress by observing tree-level decrease of stomatal conductance during sunny days as soil-moisture deficit progresses. We use the Penman-Monteith (PM) formulation to calculate stomatal conductance given observed atmospheric forcing: air temperature, humidity, net radiation, soil heat flux, and aerodynamic resistance. Such PM-based approach effectively decouples changes in evapotranspiration due to atmospheric forcing vs. changes due to decreased stomatal conductance. Multiple years of sap-flow measurements in tens of trees of multiple species allow us to identify the species-specific characteristics of the onset of stress, and the hysteretic dynamics of stomatal conductance. The daily hysteresis indicates the severity of stress. Longer-term inter-day hysteresis of the relationship between noon-time stomatal conductance and soil moisture, before and after rain have alleviated the moisture stress, indicates species-specific strategies of hydraulic-stress recovery. Recovery time is related to the degree of stress, and can vary between a nearly reversible state and 1 to 2 days of recovery, to a long recovery of several days. We find large differences between species in the sensitivity to stress and in the strength of coupling between stem water content and stomatal conductance. These are consistent with the hydraulic strategy of the trees along the an/isohydric continuum.

Identifying the hydraulic characteristics of water stress and direct observations of the coupling between stem water storage, conductance, and transpiration provide key observations with which to tune hydrodynamic models and allow process-based functional-type parameterization of stomatal conductance that accounts for tree hydrodynamics and hydraulic stress recovery.