Improving the simulation of the hysteresis of transpiration through biomass hydraulic capacitance

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Introduction

The newest generation of advanced vegetation hydrodynamics models mechanistically simulates water flow through the xylem system of trees for the purpose of more accurate predictions of transpiration. Some these new models, such as the FETCH2 model [1], can resolve changes in biomass water content along with dynamic changes to hydraulic conductance and capacitance. This skill enables the hydrodynamic models to resolve the fast dynamics transpiration at a level currently unattainable through the semi-empirical formulations within land-surface models. One of the central benefits of resolving temporal fluctuations in biomass water content is the enhanced ability to simulate the diurnal hysteresis of transpiration – a property frequently lacking in current land-surface model output [2]. Natural hysteresis is determined by both biotic and abiotic factors, and is controlled hydrodynamically when more transpiration occurs early in the day when capacitance is high, than later in the afternoon when stem-stored water has become depleted [3, 4]. New, *in situ* measurements of stem water storage dynamics provide a critical source of data with which to evaluate such plant hydrodynamic models. The availability of both new modeling and measurement technologies will improve our understanding of species' water status regulation in response to drying soil and drought.

Approach – Measurement and Modeling

We present observations from a three-year long study of stem capacitance dynamics in five species in a mixed deciduous northern forest in lower Michigan. Stem capacitance was observed as volumetric water content using frequency domain reflectometry-style capacitance sensors [5, 6]. The site receives ~800mm of rainfall annually, but water potential in the well-drained sandy soil nears the permanent wilting point several times during a hydrologically regular year. We demonstrate radical differences in the use of stored water to buffer the transpiration stream between drought tolerant and intolerant species. Red maple, a drought intolerant, isohydric species, showed a strong dependence on stem capacitance for transpiration during both wet and dry periods. While red oak, a more drought hearty, anisohydric species, was much less reliant on water storage during all conditions. During well-watered conditions, withdrawal from storage by red maple was ~10 kg day^{-1}, yet storage withdrawal from similarly sized red oaks was ~1 kg day^{-1}. Red oaks only drew strongly upon stem water storage during periods of extremely dry soils (< 4% volumetric water content).

In addition to species-specific biotic controls, stem capacitance exhibits dependence on abiotic factors of vapor pressure deficit and soil water content. Metrics of vegetation hydration status derived from dynamic changes in biomass water content can provide a means to explore forest health and specifically the response and recovery periods during and after droughts. For example, declines in maximum diurnal stem capacitance between consecutive days can indicate when a plant is unable to completely replenish depleted capacitance due to low soil water potentials, and can be used to mark the onset of hydraulic stress (Fig 1). Capacitance dynamics can likewise be used after drought to directly quantify the recovery period for hydraulic function as the time it takes for stem water content to return to observed pre-drought volumes. Analysis of the withdrawal and depletion of stem water storage demonstrates a clear threshold response to declining soil water availability.

We pair these data and concurrent sap flux, soil moisture, and eddy covariance measurements with FETCH2 tree-level simulations to test the model's ability to replicate biomass water content in response to changing atmospheric and soil moisture conditions throughout the growing season. We also evaluate the model's skill at predicting the fast (hourly) dynamics and diurnal hysteretic patterns of transpiration from different species under different meteorological conditions.

Results

The FETCH2 model is able to simulate species-specific differences in transpiration magnitude and timing in response to a variety of soil and atmospheric conditions along a wet to dry gradient. With proper parameterization of hydraulic traits, the model can replicate realistic diurnal patterns of hysteresis. The incorporation of the FETCH2 model into land-surface modeling schemes is poised to improve our ability to predict transpirative fluxes at both short and long time scales in response to our changing global climate.

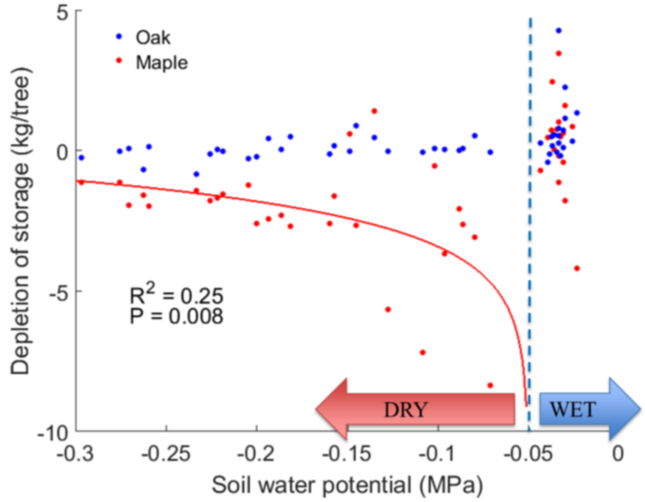

Figure 1: Stem-water storage depletion between consecutive days demonstrates a strong relationship with declining soil water potential for drought intolerant red maple, whereas oak storage remains virtually constant throughout the growing season.

References

[1] Mirfenderesgi, G., et al., *Tree level hydrodynamic approach for resolving aboveground water storage and stomatal conductance and modeling the effects of tree hydraulic strategy.* Journal of Geophysical Research: Biogeosciences, 2016. **121**(7): p. 1792–1813.

[2] Matheny, A.M., et al., *Characterizing the diurnal patterns of errors in the prediction of evapotranspiration by several land-surface models: an NACP analysis.* Journal of Geophysical Research: Biogeosciences, 2014. **119**(7): p. 1458-1473.

[3] Zhang, Q., et al., *The hysteretic evapotranspiration—vapor pressure deficit relation.* Journal of Geophysical Research: Biogeosciences, 2014. **119**(2): p. 125-140.

[4] Matheny, A.M., et al., *Species-specific transpiration responses to intermediate disturbance in a northern hardwood forest.* Journal of Geophysical Research: Biogeosciences, 2014. **119**(12): p. 2292-2311.

[5] Matheny, A.M., et al., *Contrasting strategies of hydraulic control in two codominant temperate tree species.* Ecohydrology, 2017. **10**(3): p. e1815.

[6] Matheny, A.M., S.R. Garrity, and G. Bohrer, *The Calibration and Use of Capacitance Sensors to Monitor Stem Water Content in Trees.* Journal of Visual Experiments, 2017.