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Global carbon and water exchange during drought reflects adaptation of rooting depth to climate and topography

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The rooting zone water storage capacity (S) defines the total amount of water available to plants for transpiration during rain-free periods. Thereby, S determines the sensitivity of carbon and water exchanges between the land surface and the atmosphere, controls the sensitivity of ecosystem functioning to progressive drought conditions, and mediates feedbacks between soil moisture and near-surface air temperatures. While being a central quantity for water-carbon-climate coupling, S is inherently difficult to observe. Notwithstanding scarcity of observations, terrestrial biosphere and Earth system models rely on the specification of S either directly or indirectly through assuming plant rooting depth.

Here, we model S based on the assumption that plants size their rooting depth to maintain function under the expected maximum cumulative water deficit (CWD), occurring with a return period of 40 years (CWD_{X40}), following Gao et al. (2014). CWD_{X40} is “translated” into a rooting depth by accounting for the soil texture. CWD is defined as the cumulative evapotranspiration (ET) minus precipitation, where ET is estimated based on thermal infrared remote sensing (ALEXI-ET), and precipitation is from WATCH-WFDEI, modified by accounting for snow accumulation and melt. In contrast to other satellite remote sensing-based ET products, ALEXI-ET makes no a priori assumption about S and, as our evaluation shows, exhibits no systematic bias with increasing CWD. It thus provides a robust observation of surface water loss and enables estimation of S with global coverage at 0.05° (~5 km) resolution.

Modelled S and its variations across biomes is largely consistent with observed rooting depth, provided as ecosystem-level maximum estimates by Schenk et al. (2002), and a recently compiled comprehensive plant-level dataset. In spite of the general agreement of modelled and observed rooting depth across large climatic gradients, comparisons between local observations and global model predictions are mired by a scale mismatch that is particularly relevant for plant rooting depth, for which the small-scale topographical setting and hydrological conditions, in particular the water table depth, pose strong controls.

To resolve this limitation, we investigate the sensitivity of photosynthesis (estimated by sun-induced fluorescence, SIF), and of the evaporative fraction (EF, defined as ET over net radiation) to CWD. By employing first principles for the constraint of rooting zone water availability on ET and

photosynthesis, it can be derived how their sensitivity to the increasing CWD relates to S. We make use of this relationship to provide an alternative and independent estimate of S (S_{dSIF} and S_{dEF}), informed by Earth observation data, to which S, modelled using CWD_{X40}, can be compared. Our comparison reveals a strong correlation (R^2=0.54) and tight consistency in magnitude between the two approaches for estimating S.

Our analysis suggests adaptation of plant structure to prevailing climatic conditions and drought regimes across the globe and at catchment scale and demonstrates its implications for land-atmosphere exchange. Our global high-resolution mapping of S reveals contrasts between plant growth forms (grasslands vs. forests) and a discrepant importance across the landscape of plants' access to water stored at depth, and enables an observation-informed specification of S in global models.