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Revealing the drought response of large-scale vegetation physiology from multiple satellite-based observations

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The frequency and the intensity of drought events have increased during the past decades in some regions, yet the implications of drought for the terrestrial vegetation functioning are not fully understood. In particular, drought in related studies has often been characterized by meteorological conditions rather than the actual soil moisture deficit. Further, previous research focused predominantly on the structural vegetation response, such that the large-scale physiological response remains poorly understood.

Here, we analyze and compare the vegetation's physiological and structural responses to drought across the globe using high-resolution daily TROPOMI sun-induced fluorescence (SIF) as a proxy for productivity, short-wavelength vegetation optical depth (VOD) as a proxy for canopy water conditions and biomass, and near-infrared reflectance of terrestrial vegetation (NIRv) during the period March 2018 - August 2021. Taking advantage of an extended soil moisture record (1979-2021, ERA5-Land reanalysis) we identify and focus on regions where severe soil moisture droughts occurred during our relatively short analysis period. Therein, we quantify and compare the amounts of SIF, VOD and NIRv changes during the early and late drought stages as well as for the recovery period. We also compute the vegetation response to short-term soil moisture changes, i.e. the vegetation sensitivity to short-term soil moisture and the respective changes during the course of droughts. The absolute changes of vegetation indices allow to disentangle physiological and structural responses, while the sensitivity analysis can quantify vegetation responses straightforward to water limitation by accounting for meteorological forcings. To infer vegetation sensitivity, we train random forest regression models at each grid cell, and apply the SHapley Additive exPlanations (SHAP) method to isolate the influence of soil moisture on vegetation from that of other meteorological variables such as temperature, solar radiation, precipitation and vapor pressure deficit.

Analyzing the absolute value changes of NIRv, SIF and VOD during the 2018 European drought and the 2020 Russian drought events, we find asynchronous responses of vegetation productivity and vegetation water content. This indicates different hydraulic regulation strategies in response to drought. Moving beyond these case studies, we quantified and averaged the vegetation sensitivity to soil moisture across many severe droughts across the globe, which reveals systematic sensitivity increases during the course of the drought. From an ecological perspective, this indicates increases in ecosystem vulnerability to drought, and can induce feedback in climate and ecosystem services. Vegetation responses to drought differ depending on different vegetation types, climate and soil conditions. In addition, we conduct carbon fluxes from eddy covariance measurements to confirm the vegetation responses to drought derived from Earth observation satellites. In summary, this study provides insights into vegetation responses to droughts at large spatial scales which can help to accurately quantify respective anomalies in terms of land carbon uptake to consequently improve climate projections.