Ecosystem Response to Water Stress:
Vulnerability of Global Carbon Cycle to Extreme Climate

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1. **What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming Decade?**

The amplification of the hydrological cycle as a consequence of the anthropogenic global change is shown to alter both the climate mean conditions and the variability and to lead to more extreme intra-annual precipitation and temperature regimes characterized by severe and persistent droughts and heat waves (Huntington et al. 2006; IPCC, 2007; IPCC 2014). Although forecasts of more extreme rainfall regimes are now being corroborated, the ecological impacts from this amplification remain incompletely understood and represent an important research challenge for the scientific community (Jentsch et al. 2007; Knapp et al. 2008). Developing a quantitative understanding of how drought stress is changing across different ecosystems and continents is critical given that the effects of increasingly variable precipitation patterns have been predicted to rival the ecological impacts of other global-scale changes, including atmospheric warming and increasing atmospheric CO_2 mole fractions (Easterling et al. 2000, Parmesan 2006, IPCC 2007; Knapp et al. 2008).

Ecosystems respond rapidly to climate extremes, but the nature of the responses are poorly understood (Allen et al. 2015; Anderegg et al. 2015a; Choat et al. 2012). For example, tree mortality, recruitment, and fire disturbances all have been shown to respond more directly to regional extremes than more gradual long-term changes in the annual mean (Choat et al. 2012). Coupled climate-carbon cycle models often assume that vegetation and ecosystem recovery from climate extremes occurs rapidly because these models do not yet adequately represent disturbance and recovery processes. Many studies have documented that ecosystem recovery to extreme events can take years to decades (Anderegg et al. 2015b; Saatchi et al. 2013; Ciais et al. 2005). This delay in recovery slows metabolic activities and vegetation growth, consequently interrupting ecosystem carbon uptake. With more persistent and severe water stress, plant mortality may increase to a level that tips regional ecosystems from a robust sink to a source of carbon, leading to a significant positive climate feedback and exacerbating climate warming trends (Friedlingstein et al. 2006).

If the carbon services of ecosystems are interrupted or decline significantly from increasing water stress, the impacts will be detrimental to human society in terms of environmental degradation, energy policies, food production and security. ***Despite the importance of water stress for ecosystem function, there are currently no direct measurements of water stress at the integrated plant canopy or community level and no capacity to systematically monitor ecosystem water stress over regional, continental and global domains.*** Critical Earth System Science challenges and questions linking the water stress to ecosystem function and response include:

1. During drought events, plants experience water stress and potential adverse ecological impacts, yet the question, ***how fast does the vegetation respond to water stress?*** has not been addressed except in a handful of in-situ studies at the scale of individual trees or within the footprint of eddy covariance towers. Responses at landscape, basin, and regional scales remain almost completely unexplored.
2. In extreme or persistent dry conditions, the evaporative demand at the canopy level cannot be met by the limited water supply at the soil level, causing reductions in plant water content, embolism, and hydraulic failure of water transport systems in vegetation, causing irreversible damages that may ultimately lead to large-scale desiccation and mortality. The question of ***how thresholds to hydraulic failure vary across a broad range of ecosystems and environments?*** remains a challenge to the science community.
3. Predicting how forest ecosystems will respond to future climate changes hinges on a quantitative understanding of the physiological mechanisms governing drought stress and the response of vegetation productivity and carbon dynamics. It is therefore important to know: ***What is the limit of drought tolerance of different ecosystems?***

2. Why are these challenge/questions timely to address now especially with respect to readiness?

Given the increasing climate variability and higher probability of extreme events, knowledge gaps regarding the behavior and potential response of ecosystems to water stress are becoming more apparent. The functional role of terrestrial ecosystems in the global carbon cycle depends strongly on rates of gross and net primary production. These fluxes, in turn, depend strongly on adequate supplies of plant-available water in soils to meet atmospheric moisture deficits driving water losses through evapotranspiration. Even relatively low levels of water stress may have adverse impacts on ecosystem productivity and predispose vegetation to mortality and shifts in community composition driven by other factors, including insect defoliation and wildfire. ***Understanding the ecological response to climate extremes requires simultaneous measurement of water stores in plant, litter, and soil compartments as well as transport from the soil to the canopy.***

Results on individual experiments suggest that 70% of 226 forest trees species over 81 sites worldwide operate with narrow hydraulic safety margins against extreme levels of drought stress (Choat et al. 2012). Therefore, these forests, potentially face long-term reductions in productivity and survival if temperature and aridity increase, as predicted for many regions across the globe (Zhang et al. 2007). These safety margins are shown to be largely independent of mean annual precipitation, indicating that there is global convergence in the vulnerability of all forests to drought, regardless of their current rainfall environment (Choat et al. 2012; Manzoni et al. 2013; Anderegg et al. 2015b). Recent mega-droughts in Amazonia and increasing mortality of trees at large scales suggest that drought-induced forest decline is occurring not only in arid regions but also in wet forests not normally considered at drought risk (Meir et al. 2010; Phillips et al. 2009; Saatchi et al. 2013).

One of the most promising methods for characterizing the sensitivity of plants to drought stress is by quantifying the strength of the liquid (hydraulic) connection between soil and leaves through the water-transporting xylem tissue (Choat et al. 2012). Measurements of the vertical water profile from root zone in soil to leaves in the canopy along different ecosystem and environmental gradients will be critical in addressing the response of ecosystems to water stress.

3. **Why are space-based observations fundamental to addressing these challenges/questions?**

To address the above questions and challenges, a systematic observational program is necessary to measure ecosystem water profiles globally on time scales that will enable the study of changing hydraulic dynamics in vegetated ecosystems. Current in-situ observations include tree-level measurements located in different field sites. There is no current capability to measure regional environmental gradients or landscape scale variations as a function of ecosystem composition, topography, and other environmental drivers.

Observations of the dynamics of water in soil-vegetation profile from space provide a unique opportunity to examine the spatial and temporal variations of ecosystem stress and drought response globally (Schimel et al. 2015). The spatial resolution of the observation must capture landscape scale variations of the ecosystems (~ 0.1-1 km) and the temporal resolution must capture daily to seasonal (3-7 days) variations. These measurements can be directed towards local early morning and late afternoon LEO overpasses (6 am, 6 pm local time) to allow sampling of the water profile at approximately the maximum level after recharge and the minimum level after daily evapotranspiration (ET) and photosynthetic activities respectively. Potential orbital complexity for diurnal observations of the water profile can provide a direct linkage to carbon assimilation processes and the mechanisms of stress, rates of recharge and recovery, and integrated ecosystem response (Golden et al. 2004; Doughty and Golden, 2008). In addition, long time series records are needed to characterize the interannual variability of the water column in soil and vegetation, and the legacy of water stress on ecosystem hydro-ecological state.

a) Whether existing and planned U.S. and international programs will provide the capabilities necessary to make substantial progress on the identified challenge and associated questions. If not, what additional investments are needed?

For the space observation of water profile in soil and vegetation, multi-frequency active microwave remote sensing measurements (radar sensors), ranging from the longest possible wavelength for root zone soil moisture to shorter wavelengths for the canopy water content are required (Moghaddam et al. 2000; Entekhabi et al. 2010; Troung-Loi et al. 2015; Saatchi and Moghaddam, 2000; lee et al. 2013; Kim et al. 2014). This approach was recommended by the decadal survey in 2007 as the spaceborne Microwave Observatory of Subcanopy and Subsurface (MOSS) mission as a key component in a future integrated water and energy cycle observing system.
A desirable approach includes a minimum of two frequencies at P-band (with a wavelength of about 70 cm) and L-band (24 cm wavelength) to enable the separation of water content among root zone, surface soil moisture, and upper canopy water pools (LeToan et al. 2011; Saatchi et al. 2011; Sandberg et al., 2011). Addition of Other frequencies such as C-band (~ 5 cm wavelength), or X-band (~ 3 cm wavelength), or Ku bands (~ 2 cm) can enhance delineation of vertical canopy water profile measurements with greater sensitivity to canopy moisture variations.
None of the current capability from NASA and other space programs (SMAP, NISAR, BIOMASS, SAOCOM, ALOS, etc.) are not designed and configured to provide daily or sub-weekly observations of water status in soil and vegetation layers over forest ecosystems globally. However, the existing and planned sensors all point to the fact that the technological readiness level for measurements of multi-frequency radar is high.

b) How to link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs?

In situ measurements at tree level but distributed along local environmental gradients in research plots or flux tower sites globally can illuminate the basic mechanisms of water profile variations over diurnal to seasonal cycles. These measurements can provide the basic information for developing the architecture, including requirements for spectral, spatial and temporal sampling. Multi-frequency radar observations from existing airborne platforms over ecosystems with different structure and environmental gradients, and large-scale field campaigns such as NASA's AirMOSS, ABoVE can provide the data necessary for developing algorithms and quantifying the uncertainty of measurements of the water profile in soil and vegetation. By combining a profiling radar system with fluorescence (from OCO-2, and follow on missions) and terrestrial water storage anomalies (from the GRACE follow-on mission), it will be possible to obtain an integrated regional perspective of carbon cycle responses to drought stress.

c) The anticipated scientific and societal benefits; and

The consequences of these changes from increasing climate extremes are immediate and are being observed in different ecosystems and environments. These changes may fundamentally alter the distribution and capacity for ecosystem goods and services, including potential degradation of NPP, water availability, and food security. Measurements of water profile in soil-vegetation layers will significantly improve integrated carbon and climate models by providing the mechanisms for predicting the legacy of drought and resilience of ecosystems. Reducing the uncertainty in predictions of ecosystem response will improve our ability to assess vulnerability and manage ecosystems sustainably.

d) The science communities that would be involved.

Understanding and monitoring the ecosystem responses to extreme water stress requires a multi-disciplinary approach than spans hydrology, ecosystem ecology, atmospheric composition, and carbon cycle communities. The new water profile measurements proposed here would enable rapid conceptual breakthroughs at the intersection of these disciplines and would require extensive integration of remote sensing, field and modeling approaches.

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