Characterizing water use and water stress to assess food and water security

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1 Introduction

The global carbon and water cycles are interconnected, and understanding this connection is critical to a proper understanding of either cycle and to assessing the vulnerabilities of both cycles to climate change. Two key elements of the connection—the impacts of water stress on ecosystem production and the impacts of ecosystem production on water availability—must be addressed through joint measurements of photosynthetic productivity and hydrological states and fluxes. Such measurements and associated analyses would have direct bearing on such issues as food and water security (particularly relevant in the context of growing populations), consumptive water use, and drought monitoring and forecasting.

1.1 Need for space-based observations

To monitor, understand and predict changes in regional patterns of vegetation stress and water availability at decision-relevant scales, our existing and planned networks of flux towers and in situ soil moisture measurements are inadequate. While certain countries or states have invested in soil moisture and flux networks, these are either absent or prohibitively sparse in the most food- and water-insecure regions of the world, such as East Africa. Therefore, space-based observations offer the best vantage point for monitoring indicators of water use and water stress.

1.2 Timeliness

The last ten years have seen substantial progress in both instrument technology and retrieval algorithms required for measuring vegetation stress and water availability. Laboratory studies and satellite measurements (GOSAT, GOME-2, OCO-2) have demonstrated that solar-induced fluorescence (SIF) and other reflective indices are indicative of photosynthetic rate or efficiency (and its limitation by stress). Evapotranspiration (ET) is now commonly estimated using energy-balance models that rely on satellite-derived surface temperature (via thermal infrared radiometer, or TIR, data) as an input, and a variety of newer detector options (microbolometers, strained superlattice arrays) now exist for TIR observations. New research shows that ET models can also be driven using surface temperature from microwave Ka band data, providing all-weather coverage. Finally, soil moisture can be retrieved using low frequency microwave data, as demonstrated by NASA's SMAP and ESA's SMOS missions.

1.3 Key Science questions

- Where, globally, does water availability currently limit ecosystem productivity (including the potential for crop production)? How and why might these water limited areas change with changing climate, population and land-use?
- Where do variations in ecosystem productivity currently modify water availability? How and why might these energy limited areas change with changing climate, population and land-use?
- What are the process mechanisms underlying these water and energy limitations that lead to plant stress responses and regional vulnerabilities?
    - How does plant stress relate to the water, energy and carbon budgets of plants and particularly crops?
    - What are the physical connections between plant metabolism and indicators of stress, such as solar-induced fluorescence (SIF), Photochemical Reflectance Index (PRI), Evaporative Stress Index (ESI), and soil moisture?
- How can we quantify the soil evaporation (E) and plant transpiration (T) components of evapotranspiration (ET), to better assess beneficial and non-beneficial water use in agricultural systems?

2 Space-based observations

2.1 Fluorescence and Narrowband Reflectance Indices

An ESA Earth Explorer 8 mission concept, Fluorescence Explorer (FLEX), recently received a unanimous recommendation (10/2015), to go forward to Phase A. FLEX will fly in tandem with Sentinel-3 and provide global land observations for the full chlorophyll emission spectrum (650-800 nm) including the red and far-red peaks, along with visible through NIR hyperspectral (plus SWIR) radiances at ~300 m spatial scale. ESA has also sponsored the FLEX's airborne prototype instrument package, HyPlant, which has provided high-resolution data in Europe and in the USA (during FLEX-US). Satellite data for far-red solar induced fluorescence (SIF) have been obtained by two European instruments (SCIAMACHY and GOME-2) and Japan's GOSAT satellite at a coarse global spatial scale (~0.5^{o}). All of these satellite missions are in sun-synchronous Low Earth Orbits (LEO) that offer near global coverage during the local mornings, which may not be optimal for stress detection, and early afternoons. Geostationary (GEO) orbits offer complementary information at a particular location by providing measurements at several times throughout the day. There are currently no planned fluorescence measurements from GEO instruments. However, coarse scale far-red fluorescence measurements may be possible from planned atmospheric missions such as the NASA EV-I 1 Tropospheric Emissions: Monitoring of Pollution (TEMPO) and the ESA Sentinel 4 will have some capabilities to measure fluorescence. These missions target areas of North America and Europe only.

2.2 Thermal Infrared Radiometers

Thermal Infrared Radiometers (TIR) measure the composite radiative temperature (T) of the soil surface and plant canopy. Methods to use spatial or temporal changes in T to retrieve the total ET flux based on energy balance considerations are well developed based on the current stock of geostationary (e.g. GOES or MSG SEVIRI: 3-5 km, 15 minute) and polar orbiting (PO) systems (e.g. MODIS: 1000 meter/daily, VIIRS: 375-750m/daily, or Landsat: 100 m/biweekly). However, the temporal support for TIR imaging at typical field scales (100 m) is inadequate for most operational applications of ET time series for water management. Additional sensors at Landsat scale are required, exploiting new, less-expensive TIR detector technologies (e.g., ECOSTRESS). Furthermore, TIR-based retrievals of land-surface temperature are limited to clear-sky conditions, severely limiting ET retrieval frequency in global regions with persistent cloud cover. Complementary all-sky T observations from microwave Ka band, although at coarser spatial resolution (15km), can provide information to fill gaps in ET retrievals during cloudy intervals.

2.3 Passive Microwave Radiometers

Passive microwave radiometers can provide important constraints to the characterization of water stress through the measurement of soil moisture (SM). NASA's SMAP and ESA's SMOS missions are currently using L-band microwave technology for accurate SM determination in all-weather conditions. Multichannel radiometers (without L-band) are part of four existing satellite programs: GCOM-W (JAXA), DMSP (DoD), GPM (NASA), and FengYun (China). These sensors complement TIR observations by enabling estimation of land surface temperature (from Ka-band) under clear and cloudy conditions. The primary limitation to current passive microwave technology is spatial resolution (~15 km for Ka-band, ~40 km for L-band). There are no known commitments from any space agency to continue passive microwave imaging capability through the timeframe covered by the upcoming Decadal Survey.

2.4 Observational synergies

To fully address the characterization of water use, a complete measurement suite (fluorescence, hyperspectral VIS/NIR, TIR, and passive microwave) is needed. Transpiration estimates from fluorescence and hyperspectral indices (e.g., the Photochemical Reflectance Index, PRI) collocated and coinciding with ET estimates from a thermal-based energy balance approach would allow for E/T separation and calculation of crop water productivity ('crop-per-drop'). Thermal infrared further bridges the spatial scales of interest to agriculture (food and water security) and global climate and weather models (climate impacts, ecosystem productivity). For the latter, more continuous sampling in clear and cloudy skies (provided by coincident passive microwave observations) is needed to close the water balance over larger domains and integrate over the growing season.

3 Linking space-based observations with other data

3.1 Calibration/Validation

All of these measurement types, but especially the fluorescence, will require calibration and validation activities. GSFC has helped support a first generation prototype field spectrometer system, called FUSION, which currently has four high spectral resolution spectrometers for fluorescence and narrow-band reflectance index measurements (e.g., PRI, EVI), and which makes unattended directional measurements throughout the day. This system could be enhanced and combined with existing field systems designed for energy and water balance measurements to provide a comprehensive and portable cal/val platform for deployment at flux towers and other key sites.

3.2 Synthesis with other platforms

The characterization of ET via plant water use and stress also facilitates the diagnosis and closure of the surface energy, water, and carbon balances from space. In terms of energy, latent heat must be balanced with the residual of net radiation (CERES, Geostationary), and sensible and ground heat flux (thermal instruments; Section 2.2). ET represents a major component of the water balance, which can be constrained by synergistic measurements of precipitation (GPM), change in water storage (SMAP, SMOS, GRACE), and catchment scale runoff (SWOT). Finally, water use and stress within plants is closely related to photosynthesis and can therefore be used in combination with vegetation type/condition (VIIRS, Sentinel-2/3) and structure (GEDI, NiSAR, BIOMASS) information to improve our knowledge of vegetation carbon uptake and vegetation vulnerability to drought (in combination with CO2 flux estimates from OCO-2).

3.3 Synthesis with Models

While land surface parameterizations used in Earth System models generally include representations of photosynthesis and its relationship to water availability, these crude representations would benefit from process understanding gleaned from analyses of the proposed measurements. Furthermore, by providing timely information on when vegetation begins undergoing water stress, the measurements can provide information on water content in the root zone, an otherwise unmeasurable (from space) quantity of critical importance to crop and weather forecast models. Recently the capability to simulate SIF within global models has been accomplished, for example in the NASA Global Modeling and Assimilation Office’s Catchment-CN model. This provides a powerful tool for evaluating model performance and offers potential new capabilities for parameter estimation or data assimilation. However, higher resolution data and a better suite of time of day measurements would enhance simulation results.

4 Anticipated scientific and societal benefits

To meet the food supply needs of the world's growing population, global food production will need to roughly double by 2050. This increased production must be accomplished within the constraints of a non-uniform distribution of freshwater resources, an amplifying climate cycle, and concern for the environmental impacts of agriculture. To make significant strides in improving the production capacity and resiliency of global agricultural systems, we must first better understand the regional distribution of factors currently limiting production and water availability. The ability to accurately quantify beneficial (T) and non-beneficial (E) components of consumptive water use (ET) is essential to improving water use efficiency in global agricultural production systems. Robust early warning indicators highlighting regions with developing crop stress and degrading canopy conditions due to drought or other stressors are needed to improve within-season yield forecasts and to more effectively mobilize humanitarian response to regional crop failures.

5 Key science communities that would be involved

Observing water stress as a key linkage between global carbon and water cycles requires experts from multiple disciplines, including ecology, hydrology, agriculture, forestry, weather and climate. Synthesis of multiple observational technologies requires science and engineering expertise in solar induced fluorescence, narrowband reflectance indices, thermal infrared radiometry and passive microwave radiometry, combined with algorithm development, and water and carbon cycle modeling and data assimilation.