

EVAPOTRANSPIRATION: A CRITICAL VARIABLE LINKING ECOSYSTEM FUNCTIONING, CARBON AND CLIMATE FEEDBACKS, AGRICULTURAL MANAGEMENT, AND WATER RESOURCES

Joshua B. Fisher¹, Elizabeth Middleton², Forrest Melton³, Martha Anderson⁴, Christopher Hain⁵, Richard Allen⁶, Matthew McCabe⁷, Jean-Pierre Lagouarde⁸, Kevin Tu⁹, Dennis Baldocchi¹⁰, Phil Townsend¹¹, Johan Perret¹², Diego Miralles¹³, Duane Waliser¹, Andrew French¹⁴, Eric Wood¹⁵, Jay Famiglietti¹, Graeme Stephens¹, David Schimel¹, Simon Hook¹

¹ Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

² NASA Goddard Space Flight Center, Greenbelt, MD, USA

³ NASA Ames Research Center, Moffett Field, CA, USA

⁴ US Department of Agriculture, Beltsville, MD, USA

⁵ NOAA National Environmental Satellite, Data, and Information Service, College Park, MD, USA

⁶ University of Idaho, Kimberly, ID, USA

⁷ King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

⁸ INRA – Bordeaux Sciences Agro, Villenave D’Ornon, France

⁹ DuPont Pioneer, Johnston, IA, USA

¹⁰ University of California, Berkeley, CA, USA

¹¹ University of Wisconsin, Madison, WI, USA

¹² EARTH University, San José, Costa Rica

¹³ VU University Amsterdam, The Netherlands

¹⁴ US Department of Agriculture, Maricopa, AZ, USA

¹⁵ Princeton University, Princeton, NJ, USA

KEY CHALLENGES/QUESTIONS The ‘Fate of the Terrestrial Biosphere’ continues to be one of the most important scientific and societal questions facing our planet. The need to address this question continues to increase in importance given recent and projected changes in climate, particularly for water resources availability and related increases in drought frequency and intensity, and an overall drying of the land surface. The response of the terrestrial biosphere to changes in climate remains one of the largest sources of uncertainty in climate projections because ecosystems can act as either carbon sinks (photosynthesis, primary production) or carbon sources (respiration, decomposition, mortality, combustion), and provide climate feedbacks through latent heat fluxes, albedo, and water cycling [Friedlingstein *et al.*, 2014]. Food and water security are increasingly under threat due to the challenge of being able to monitor and understand how our agricultural systems are responding and should be managed under changing hydrological and climatological regimes [IPCC, 2014].

Most hydrological studies have tended to focus on the supply side of the water ‘coin’ (e.g., precipitation, snow, soil moisture, groundwater), yet have largely ignored the demand side (i.e., evapotranspiration or ET, the loss of water to the atmosphere). However, increasing droughts and water demands have now made it critical to understand both sides of this ‘coin’, particularly the consumptive use and subsequent loss, and vegetation stress response, of water through ET—the overwhelmingly dominant use of water (Figure 1). ET is a keystone climate variable that uniquely links the water cycle (evaporation), energy cycle (latent heat flux), and carbon cycle (transpiration–photosynthesis tradeoff) [Fisher, 2013]. ET is the leading climatic predictor of biodiversity [Fisher *et al.*, 2011], and the dominant requirement for agricultural water management (irrigation so that ET approximates atmospheric demand) [Allen *et al.*, 1998; Anderson *et al.*, 2011]. Critical Earth System Science challenges and questions linking ET to the overall objective of understanding the fate of the terrestrial biosphere include:

- How are natural and managed ecosystems responding to changes in climate and water availability?
- How much water do different types of plants use?
- What is the timing of plant water use, and how does that vary diurnally, seasonally, and annually?
- Which areas evaporate more or less water than other areas?
- How does ET redistribute water in the hydrological cycle?
- How do changes in ET amplify or dampen climate feedbacks and hydrometeorological extremes at local to regional scales?
- Are we witnessing observable changes in hydrological fluxes and acceleration, and if so, what are the causes and consequences of these?
- Can we unify the water, carbon, and energy cycles globally from spaceborne observation with ET as the linking variable?
- How should water and ecosystem management adapt to changes in hydrological and climate variability?
- What information do we need to optimize food security, crop productivity, and water security in a changing climate to meet the demands of a growing population?

TIMELINESS In 2005, the worst drought in recorded history enveloped the Amazon basin, reversing the long-term carbon sink into a carbon source. In 2010, an even stronger drought hit the Amazon basin, which had not fully recovered from the drought 5 years earlier [Saatchi *et al.*, 2013]. In 2011, the worst drought in decades hit the US Midwest [Long *et al.*, 2013] and was followed in 2012 by an even worse drought that impacted 80% of US agriculture [Mallya *et al.*, 2013]. From 2012-present, many sectors of California's agriculture have ceased due to a multi-year mega-drought, resulting in depleted surface storage and groundwater aquifers [AghaKouchak *et al.*, 2014]. Globally, large tracts of boreal forests are drying and becoming increasingly susceptible to fire [Soja *et al.*, 2007], and temperate forests in close proximity to high population centers are dying from lack of water [Schwalm *et al.*, 2012].

The hydrological cycle is rapidly changing, resulting in greater variance and more extremes. Our collective infrastructure is not equipped to buffer these changes in water availability, with storage and supply now outpaced by demand. US drought predictive capabilities missed the 2012 US Midwest drought magnitude and intensity. While many ecosystems may be unable to adapt to such changes, human society has the potential to adapt given the right information at the right time. The deficiency of the US drought predictive capabilities was due in large part to missing information on land-atmosphere coupling, i.e., ET, and an under-emphasis on the response of vegetation to drought. One of the few drought metrics to capture the drought magnitude, intensity, and timing (i.e., early-warning indicator) at resolutions applicable for management was based on ET: the Evaporative Stress Index (ESI) [Anderson *et al.*, 2010]. Water managers need to know now how to allocate dwindling water resources to benefit society and optimize productivity, and mitigate economic, societal, legal, and ecological damage. With a global population of 9B people by 2050, we will need a 60% increase in food production with a commensurate increase in water from an already stressed hydrological system [IPCC, 2014].

Starting in the short-term, we need to maximize and optimize our critical information gathering on plant–water dynamics to ensure food security and water security, and provide key and timely feedbacks to climate and biospheric model responses to a changing climate. The science communities that would capitalize on this information on ET include, in part: I) Agronomy; II) Ecology; III) Hydrology; IV) Atmospheric; V) Climate; VI) Carbon Cycle; VII) Coastal; VIII) Computer/Data Science; IX) Statistical; and, X) Policy/Economics.

SPACE-BASED OBSERVATIONS The space-based challenge necessary to capture the key science questions on ET dynamics described above demands rigorous observation across nearly all facets of remote sensing:

- *High spatial resolution*: length scales required to detect spatially heterogeneous responses to water environments; i.e., “field-scale” agricultural plots, narrow riparian zones, mixed-species forest/ecosystem assemblages;
- *High temporal resolution*: ET is highly variable from day to day, thus management necessitates accurate ET information provided in sync with daily irrigation schedules; ET also varies throughout the day, particularly under water stress, when vegetation may or may not shut down water use by closing leaf stomata pores;
- *Large spatial coverage*: global coverage enables detection of large-scale droughts and is necessary for climate feedbacks and closing the global water and energy budgets; ensures consistency in measurements across regions and shared resources;
- *Long-term monitoring*: droughts and drought responses evolve over the course of multiple years; as climate becomes increasingly variable, the need for long-term observations will be increasingly critical.

ET is a multi-faceted variable controlled by a combination of vegetation, atmospheric, and radiative drivers obtainable from remote sensing [Fisher *et al.*, 2008]. Phenology and vegetation cover are necessary for seasonal dynamics and relative magnitudes of ET fluxes. Humidity and air temperature dictate the diffusion of water from the land to the air. Net radiation and land surface temperature provide the physical drivers for the state change of water and the subsequent impact on latent and sensible heat partitioning. Critical ground-based observations also synergize to complete the picture: agricultural practices (irrigation type/management, planting decisions, nutrients, soil composition, tilling practices, seed types), water quality, plant plasticity/sensitivity/adaptation response, and computational models (crop, climate, water). The key information flow or logic pipeline that needs to be fully captured can be distilled to the following: Stress → Yield → Mortality → Management; this flow, in turn, cycles through itself.

A few current and planned space missions/instruments capture some, but not all, of the components necessary to meet the requirements for addressing the key science questions, challenges, and societal benefits described above. For example, Landsat provides excellent spatial resolution, but poor temporal resolution. MODIS/VIIRS provide good re-visit time, but insufficient spatial resolution. GOES captures the diurnal cycle, but at the expense of spatial resolution and coverage. ECOSTRESS will provide excellent spatial, temporal, and spectral resolutions, but is not an extended mission and does not capture the high latitudes. Sentinel provides moderate spatial and temporal resolutions. The proposed HyspIRI mission, identified as a Tier 2 mission in the 2007 Decadal Survey, can provide excellent spatial resolution, good temporal resolution, and global coverage, but is not designated a Tier 1 mission.

RECOMMENDATIONS Given the existing and planned US and International Programs that help contribute to the science requirements described above, the primary take-home points of this White Paper are that in future measurements to support ET:

- We need to improve the frequency of revisits;
- We need to resolve the diurnal cycle;
- We need to maximize spatial resolution and coverage.

While it is unlikely that a panel focused solely on ET or plant–water dynamics is formed, given the cross-cutting nature of this variable we highly recommend that multiple ET experts are selected as members on the panels the NRC decides to form. This could be across terrestrial hydrology, ecosystems/ecology, agriculture/societal benefits, climate, and land–atmosphere connections/synergies, for example. It is critical that ET features as an important element of such panels. The science recommendations and discussion throughout this White Paper will hopefully serve as key anchor points for the Decadal Survey structure and guidance, as well as follow on RFI solicitations to the Decadal Survey panels.

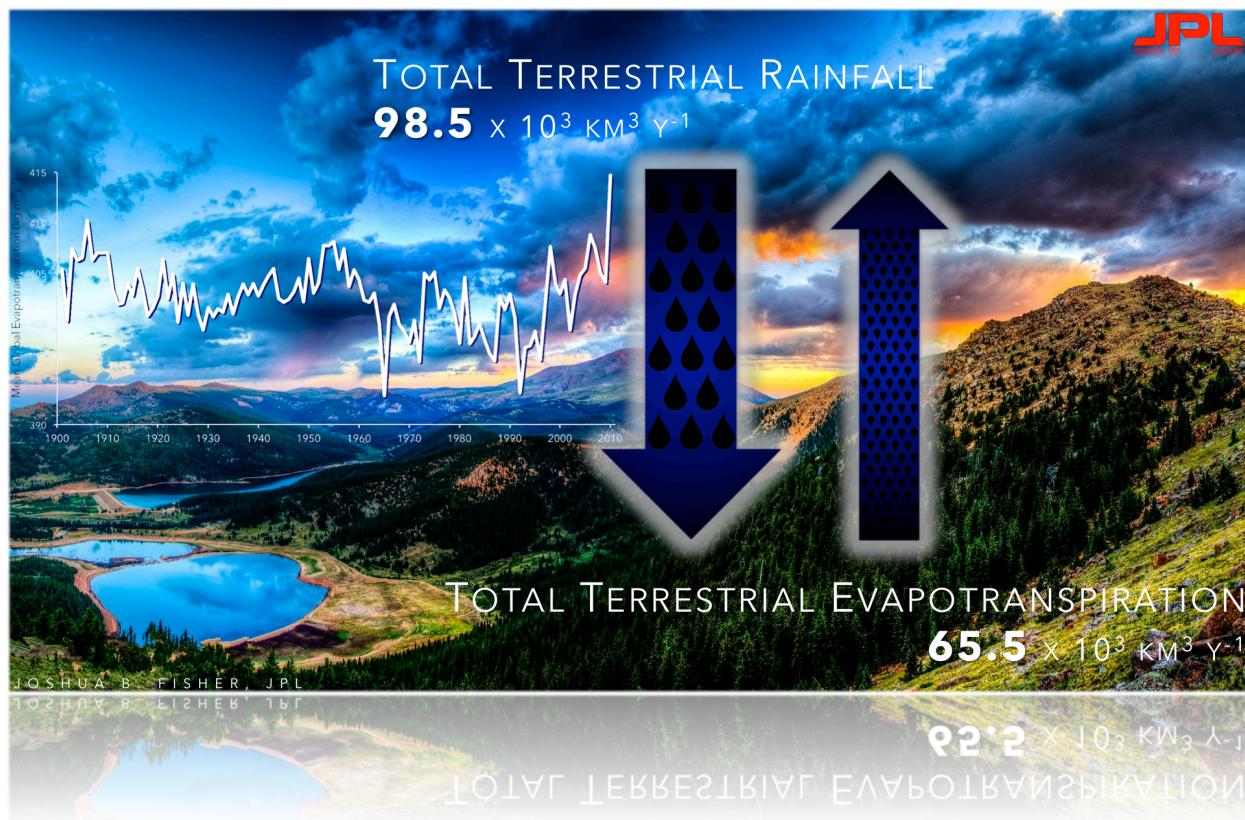


Figure 1. Terrestrial evapotranspiration (ET) consumes two-thirds of total global terrestrial precipitation [Oki and Kanae, 2006], and the trajectory of ET is highly uncertain [Mao et al., 2015]. Background image from hdwallpapers.cat.

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