EVAPOTRANSPIRATION:

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

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SCIENCE & APPLICATION TARGET 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 by an even stronger drought in 2012 that impacted 80% of US agriculture [*Mallya et al.*, 2013; *Wolf et al.*, 2016]. Since 2012, many sectors of California's agriculture have been significantly reduced by a multi-year mega-drought, resulting in depleted surface storage and groundwater aquifers [*AghaKouchak et al.*, 2014]. Such regional extremes are occurring across diverse ecosystems, additionally with large tracts of boreal forests 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. 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. Nonetheless, our collective infrastructure is not equipped to buffer these changes in water availability, with storage and supply now increasingly outpaced by demand. US drought predictive capabilities failed in its forecast of the 2012 US Midwest drought magnitude and intensity. The failure of the US drought predictive capabilities was due in large part to missing information on land–atmosphere coupling, i.e., evapotranspiration (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; *Otkin et al.*, 2016]. 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. Such resource allocation problems become even more pressing with projections that a global population of 9B people by 2050 will need a 60% increase in food production with a commensurate increase in water supplied from an already stressed hydrological system [*IPCC*, 2014].

The science and application targets described here focus on natural and managed terrestrial ecosystems, as well as the hydrological cycle and water resources (e.g., the *Marine & Terrestrial Ecosystems Panel*, and the *Global Hydrological Cycle & Water Resources Panel*). ET also plays a critical role in fine scale weather, affecting turbulence and cloud formation. In addition, changes in ET can be used to diagnose climate variability and change, e.g., whether the land surface wets or dries over decadal scales [*Greve et al.*, 2014]. As such, ET-based science and application targets cross-cut four of the five Decadal Survey Panels through all of the working groups (Figure 1), highlighting the importance of this key variable.

UTILITY OF THE MEASURED GEOPHYSICAL VARIABLE The high priority geophysical variable to be measured here is evapotranspiration (ET), which is the keystone climate variable that links the water cycle (evaporation), energy cycle (latent heat flux), and carbon cycle (transpiration–photosynthesis tradeoff) [*Monteith*, 1965; *Fisher*, 2013]. ET is the largest climatic predictor of biodiversity [*Fisher et al.*, 2011], the predominant requirement for agricultural food production and water management [*Allen et al.*, 1998], and the leading indicator of extreme event flash droughts [*Anderson et al.*, 2013]. The 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 plant assemblages in ecosystems use?
- What is the timing of water use among ecosystems, and how does that vary diurnally, seasonally, and annually?
- 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 there 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 observations with ET as the linking variable?
- What global science guidance can assist decision makers for water and ecosystem management, to adapt to changes in hydrological and climate variability?
- How can information on ET be optimized to optimize food security, crop productivity, and water security in a changing climate to meet the demands of a growing population?

The science and applications objectives that map on to these questions require the space-based measurement of ET dynamics across high spatial and temporal resolutions, and across large space and time domains. As soon as possible, we need to maximize and optimize our critical information gathering on plant–water dynamics to ensure food and water security, and provide key and timely data-driven feedbacks to climate and biospheric model responses to a changing climate.

ET is a major focus of the US National Research Council (NRC), including the previous Decadal Survey, the World Climate Research Programme (WCRP), the US Global Change Research Program (USGCRP), and NASA Earth Science programs for Carbon Cycle and Ecosystems, as well as Water and Energy Cycle, focus areas. The science communities that would capitalize on improved 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. ET is also a major target of the NRC Decadal Survey HyspIRI and Landsat missions [*US NRC*, 2013]. Water limitation and droughts, in addition to biome response and climate sensitivity, are specifically called out in:

- **Decadal Survey**: *recommended observations, key questions and science themes* [*US NRC*, 2007; Chapter 2: p27; Chapter 7: p196];
- **WCRP**: *grand science challenges* [*WCRP*, 2012];
- **NASA Earth Science**: *big questions* [*NASA Earth Science*, 2013].

Plant–water dynamics and the functioning of terrestrial ecosystems are encompassed within:

- **Decadal Survey**: *role of satellites in understanding ecosystems* [*US NRC*, 2007; Chapter 7: p192; Chapter 9: p257];
- **NASA Terrestrial Hydrology, Ecology, and Carbon Cycle Programs**: *primary scientific objective* and *goals* [*e.g., A.20-1 ROSES*].

Agricultural applications and water management are specifically called for in:

- **NRC**: *"Global Change and Extreme Hydrology"* [*US NRC*, 2011], *"Assessment of Intraseasonal and Interannual Climate Prediction and Predictability"* [*US NRC*, 2010], and *"Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program" [US NRC, 2013]* ;
- **Decadal Survey**: *key questions and science themes* [*US NRC*, 2007; Chapter 7: p196]; and
- **USGCRP**: *strategic goals* [*USGCRP*, 2012].
- **White House**: *National Drought Resilience Partnership* [*USGCRP*, 2012]

QUALITY REQUIREMENTS 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 information is necessary for seasonal dynamics and relative magnitudes of ET fluxes. Humidity and air temperature regulate the transfer of water from the land into 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. Important ground-based observations synergistically complete the picture: agricultural practices (irrigation type/management, planting decisions, nutrients, soil composition, tilling practices, seed types), water quality, plant plasticity/sensitivity/adaptation response—all of which are coupled with computational models (crop, climate, water). The quality requirements for ET measurement to achieve the science and applications objectives and targets that address the science questions include:

- *High accuracy*: the higher the accuracy, the greater the ability to differentiate water use and stress among different crops, species, and ecosystems, as well as enable more efficient water management (<10% relative accuracy);

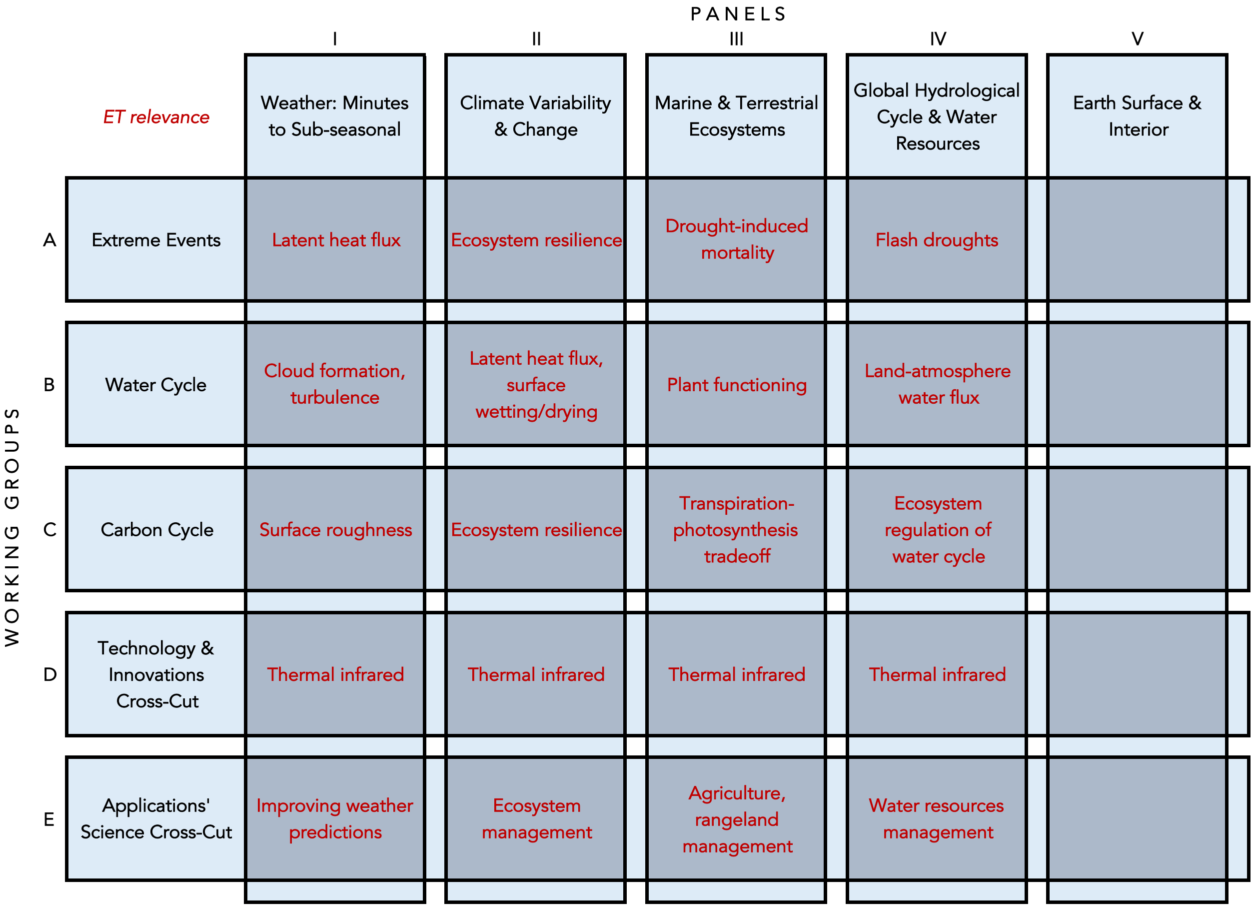
- *High spatial resolution*: length scales required to detect spatially heterogeneous responses to water environments; i.e., "field-scale" agricultural plots, narrow riparian zones, mixed-species forest/ecosystem assemblages (<100 m);
- *High temporal resolution*: ET is highly variable from day to day, 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 (daily, diurnal);
- *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 (global land);
- *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 likewise be increasingly critical (decadal).

Because ET cannot be measured directly as a water variable, it must be measured as an energy variable (i.e., the latent heat flux) with multiple types of measurements necessary to ensure that the abiotic and biotic controls are adequately captured. One critical measurement of importance to the estimation of ET is thermal infrared (TIR) measurements of land surface temperature, as these capture fine spatial and temporal dynamics associated with heterogeneous land surface processes controlling ET. TIR measurements across multiple bands (>4) ensure that the land surface temperature and emissivity variables are retrieved to a fidelity of within 1K accuracy (assuming a precision of 0.3K), allowing TIR-derived uncertainty within ET estimates to be within the 10% relative accuracy that is necessary to differentiate stress/non-stress and vegetation types/conditions [*Hook et al.*, 2004; *Hook et al.*, 2005; *Blonquist Jr et al.*, 2009; *Hulley and Hook*, 2009; *Cammalleri et al.*, 2012; *Hulley et al.*, 2012; *Fisher et al.*, 2013]. These should be acquired at high spatial resolutions (<100 m) and high temporal resolutions (daily, diurnal), as justified above [*Allen et al.*, 2007; *Chen et al.*, 2008; *Allen et al.*, 2011; *Anderson et al.*, 2012]. Commensurate and collocated visible and near infrared (VNIR) measurements for phenology and vegetation cover are required at high spatial resolutions (<100 m), though temporal resolutions (<weekly) may be less than that of TIR due to the difference between phenological change (relatively slow, VNIR) versus physiological functioning (relatively fast, TIR) [*Anderson et al.*, 1997; *Allen et al.*, 2007; *Fisher et al.*, 2008; *Allen et al.*, 2011]. High quality and high resolution meteorology help differentiate microclimates, though in general meteorological variables are well-mixed relative to the much more heterogeneous land surface variables, so meteorological spatial resolution requirements may be less stringent (<5 km), although temporal resolution requirements remain high (daily, diurnal) [*Anderson et al.*, 1997; *Allen et al.*, 2007; *Fisher et al.*, 2008; *Allen et al.*, 2011].

AFFORDABILITY 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 (>60 m), but poor temporal resolution (16 days). MODIS/VIIRS provide good re-visit time (daily), but insufficient spatial resolution (≥750 m). GOES captures the diurnal cycle, but at the expense of spatial resolution (>3 km) and coverage. ECOSTRESS will provide excellent spatial (70 m), temporal (3-5 days, diurnal sampling), and spectral resolutions (5 bands), but is not an extended mission (1 year) and does not capture the high latitudes. ESA's Sentinel-2 provides good spatial and temporal resolutions in the visible to shortwave spectrum (10-60 m 5 days), but has a similar TIR spatial resolution as MODIS/VIIRS. The proposed HyspIRI mission, identified as a Tier 2 mission in the 2007 Decadal Survey, can provide excellent TIR and visible spatial resolution (60 m), good temporal resolution (5 days), and global coverage, but is only in Pre-Phase A. The instrumentation and data algorithms for ET are mature; it is only the flight coverage that needs to be improved and optimized. An orbital mission to support ET capability from space draws upon extensive heritage and demonstrated need.

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 measurements to support ET are critical, and in the future we need:

- The frequency of revisits to capture physiological onset of stress;
- To resolve the diurnal cycle to improve water management;
- The spatial resolution and coverage to capture land surface heterogeneity.



PANELS

WORKING GROUPS

	ET relevance	I Weather: Minutes to Sub-seasonal	II Climate Variability & Change	III Marine & Terrestrial Ecosystems	IV Global Hydrological Cycle & Water Resources	V Earth Surface & Interior
A	Extreme Events	Latent heat flux	Ecosystem resilience	Drought-induced mortality	Flash droughts	
B	Water Cycle	Cloud formation, turbulence	Latent heat flux, surface wetting/drying	Plant functioning	Land-atmosphere water flux	
C	Carbon Cycle	Surface roughness	Ecosystem resilience	Transpiration-photosynthesis tradeoff	Ecosystem regulation of water cycle	
D	Technology & Innovations Cross-Cut	Thermal infrared	Thermal infrared	Thermal infrared	Thermal infrared	
E	Applications' Science Cross-Cut	Improving weather predictions	Ecosystem management	Agriculture, rangeland management	Water resources management	

Figure 1. Evapotranspiration (ET)-based science cross-cuts across 4 of the 5 Decadal Survey panels and all 5 of the working groups. The specific science and application targets enabled by ET measurements are highlighted in red within each panel and working group:

IA) The latent heat flux, functionally equivalent to ET, is a driver of fine-scale weather and is impacted by extreme events, particularly heat waves and droughts;

IB) ET provides the primary terrestrial water input for cloud formation as well as turbulence;

IC) ET defines, in part, the type of vegetation that can grow in any given area, and the type of vegetation defines the surface roughness, which affects wind;

ID) Thermal infrared technology and innovations, in particular, will help provide the data to inform understanding of weather;

IE) ET influences weather and subsequent weather predictions;

IIA) Ecosystem water use requirements determine the resilience to extreme events such as droughts, which also impact their ability to feedback to climate through water release and carbon uptake;

IIB) ET is a key component to net surface wetting or drying, and is also the latent heat flux that contributes to the total surface energy balance;

IIC) Like IIA, but for longer term mean conditions;

IID) Thermal infrared technology for reducing uncertainty in climate variability and change;

IIE) Ecosystems can be managed based on water requirements, which can impact climate;

IIIA) Ecosystem water use and requirements are critical for understanding vulnerability to droughts;

IIIB) Plant functioning controls water use;

IIIC) Water loss through transpiration means carbon uptake for photosynthesis, and vice versa;

IIID) Thermal infrared technology to characterize terrestrial ecosystems;

IIIE) ET is a top priority for agriculture and rangeland management, as well as other applications (e.g., fire);

IVA) ET is the leading predictor of flash droughts;

IVB) ET is the main water cycle pathway that returns water to the atmosphere;

IVC) Equivalent to IIIC;

IVD) Thermal infrared technology for capturing a major water cycle component and a critical variable in quantifying water resources;

IVE) ET, as the major water loss pathway, is a key variable for water resources management.

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