Response to the Initial Request for Information for the initiation of the 2017-2027 Decadal Survey for Earth Science and Applications from Space

Burning Questions: Critical Needs for Remote Sensing of Fire Impacts on Ecosystems

Summary: This paper summarizes critical Earth science questions related to fire processes. New types of space-based observations are required to advance our understanding of fire impacts on the carbon and water cycles, ecosystem processes, and ecosystem services. These new observations are urgent due to rapidly changing fire regimes, ecosystems and climate.

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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?

Fire is the most important disturbance agent in the terrestrial biosphere. In many regions, fire regimes have undergone rapid changes as a consequence of warming and increasing anthropogenic modification of ecosystems. Changes in fire behavior, occurrence, size, and severity have direct, critical impacts on the carbon cycle (emissions and productivity), the water cycle (evapotranspiration and runoff), ecosystem processes (composition, structure, and fluxes) and ecosystem services (air quality, water quality, and infrastructure). Using coarse (e.g. MODIS, VIIRS) and moderate (e.g. Landsat) spatial resolution multispectral satellite imagery, we can currently observe where and when fires occur, and monitor coarse-scale ecosystem changes in response to fire disturbance. However, our ability to understand fire as an ecological process is limited by current measurement capabilities. To advance our knowledge of fire and its influence on the carbon and water cycles, ecosystems, and human systems, we must answer the following questions:

- *What are the total global carbon emissions from fires, accounting for spatial variability in pre-fire fuel conditions and fire severity, and including emissions from agricultural and understory forest fires?*
- *How do fuel type, fuel condition, fuel moisture, and soil moisture influence fire occurrence, behavior, and severity?*
- *How do fire severity and intensity influence vegetation composition and carbon sequestration during post-fire recovery?*
- *How does fire alter ecosystem services of clean air and water, habitat, and biodiversity, and which regions are most vulnerable to these changes?*
- *How can we adaptively manage ecosystems to increase ecosystem resilience and balance multiple ecosystem services?*

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

Ecosystems and fire regimes are rapidly changing at historically unprecedented rates. Wildfire activity has significantly increased in boreal forest ecosystems and declined in savannas. Agricultural fires are an increasing threat to sustainably managing tropical forests and peatlands. In many regions, fire is an important regulator of biodiversity, and recent changes in fire regime have caused permanent shifts in species composition. These ecological changes have implications for biodiversity, land use, carbon and water cycling, and Earth's climate. Intensification of the fire regime in many areas contributes to increasing atmospheric carbon dioxide, while vegetation regrowth following fire can be a multi-decadal carbon sink. Billions of dollars are spent each year fighting and managing fires, meaning potential exists for selective fire management to target critical ecosystem services. Yet proper scientific understanding of fire impacts on ecosystems is lacking. It is urgent that we improve our understanding of fire processes and impacts while these rapid changes are occurring, enabling improved understanding of future ecosystem changes and providing science-based and data-driven information for improved resource management strategies and practices.

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

Global, space-based observations are essential to addressing the science questions listed above due to global diversity in fire processes. Fire occurs in ecosystems that range from tropical rainforests to deserts, and exhibits a variety of forms from canopy fires to long duration "ground" fires in organic soils. Fire occurrence, fire behavior, fire severity, and subsequent vegetation recovery vary tremendously. Current understanding of fire processes through space-based observation has primarily relied on coarser spatial resolution (MODIS, VIIRS, GOES) and moderate spatial resolution (Landsat) multispectral observations covering visible, near infrared (NIR; 0.7-1.4μm), shortwave infrared (SWIR; 1.4-2.5μm), mid infrared (MIR; 3-5μm), and thermal infrared (TIR; 8-12μm) spectral regions. While valuable, these observations have limited capacity to: i) measure canopy water content or soil moisture, important indicators of fire danger; ii) identify fuel types and vegetation functional types that help determine ecosystem recovery following wildfire and fire severity, behavior, and emissions; or iii) detect and measure temperature of low intensity and smaller fires that have critical impacts on carbon emissions and air quality. Current observing systems also have limitations for advancing our understanding of climate, weather, and fuel controls on fire behavior.

Imaging spectroscopy has demonstrated capabilities for characterizing fuel types, vegetation senescence, fire severity, and ecosystem recovery. Narrow spectral features in the SWIR spectral region allow detailed canopy moisture retrievals. Using seasonally acquired measurements of fuel moisture, the effects of pre-fire moisture conditions on fire behavior and fire severity can be evaluated. Imaging spectroscopy also permits sub-pixel fire severity assessments, allowing detailed discrimination between the green (live vegetation), brown (senescent or scorched vegetation), and black (charred vegetation) components of a post-fire landscape. For post-fire recovery, imaging spectroscopy can capture ecosystem composition during succession. Coupled with detailed information on pre-fire conditions and fire severity, this can add critical constraints to carbon cycle models and refine estimates of carbon emissions, post-fire carbon sequestration, and impact of changing fire regimes on the land carbon sink. A space-based imaging spectrometer with a 30 m spatial resolution would provide continuity for global landscape-scale mapping, and the additional "bonus" of Landsat TM/ETM+/OLI equivalent products created from finer spectral resolution data would facilitate broader Earth system science and application. A global mapping imaging spectrometer would be unique in its capabilities and coverage; the European PRISMA and EnMAP imaging spectrometers are sampling missions without global mapping capabilities.

Multispectral SWIR, MIR, and TIR data are essential for detecting fires and measuring fire temperature. They can also be used to derive metrics of evapotranspiration and water stress, which can be indicative of fire risk and influence fire occurrence, severity and intensity. Current global mapping sensors (e.g. MODIS, VIIRS) do not have the spatial resolution or sensitivity required to detect many smoldering fires (lower temperature fires covering larger areas) and understory forest fires, and therefore our knowledge of their potential role in forest degradation and as an emission source is limited. High spatial resolution maps of fire temperature will allow improved estimates of combustion efficiency and resultant carbon and particulate emissions. Mapping fires and their instantaneous emissions requires consistent global mapping at a spatial resolution of 60 m or finer, along with multiple bands to characterize fire temperature and for temperature-emissivity separation. A global mapping multispectral MIR/TIR sensor would be unique in its capabilities and coverage, since ASTER and ECOSTRESS multispectral TIR sensors are sampling missions, and all other TIR sensors have spatial resolutions coarser than 100 m. While current geostationary missions (GOES) offer advantageous temporal resolutions for studying fire behavior over time, their spatial resolution is far too coarse for this purpose. High spatial resolution SWIR and MIR spectrometers in geostationary orbit would improve our understanding of weather controls on fire behavior, and subsequent linkages with post-fire impacts on mortality and carbon losses.

Metrics calculated from synthetic aperture radar (SAR) data have been related to in-situ biomass and organic soil moisture, an important consideration for fires in peatlands and forests where deep organic soils are the primary pools of carbon. Polarimetric SAR has shown value for estimating surface fuel moisture and quantifying vegetation biomass. There has not been a US polarimetric SAR system in orbit providing the data needed for a full exploration of polarimetric SAR for biomass and soil moisture retrieval, and future planned non-US SAR missions will not carry fully-polarimetric systems. Due to the multi-use nature of the future NISAR mission, full polarimetric image collection is planned for agricultural zones only and will not be collected in the most fire-prone regions.

While significant scientific advances in fire science are to be expected from the availability of one of these individual sensors, synergistic observation with multiple systems may further enable scientific discoveries. For example, canopy moisture content retrieved from imaging spectroscopy and water stress derived from TIR data provide complementary information with regards to fire risk. Combined observations could establish and quantify relationships between fuel type, fuel condition, canopy moisture content, soil moisture, and fire severity and ecosystem recovery. Monitoring surface soil moisture with SAR in conjunction with imaging spectroscopy would add to the information needed to model pre-fire fuel moisture status and post-fire ecological condition. Imaging spectroscopy, TIR, and SAR data could also complement missions to measure vegetation structure and continued monitoring and modeling of global vegetation productivity.

Measuring the critical impacts of fire on the carbon cycle, water cycle, ecosystem processes, and ecosystem services will require extensive collaboration across multiple disciplines within Earth System Science (e.g. terrestrial and fire ecology, biogeosciences, atmospheric chemistry and physics, geomorphology, hydrology). NASA has a long history of promoting successful applications related to fire activity and disturbance, and answering these questions will enable new applications that will benefit the fire and resource management communities. Improved understanding of fire processes will have direct societal benefits, including improved understanding of fire hazard and management of natural resources and ecosystem services.