The role of fire in the Earth System

2017 Decadal Survey
Response for Information #2

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Question 1, Part (A) – Fire Science and Application targets

Key questions regarding the role of fire in the Earth system (Figure 1) include:

A. How does fire affect ecosystem services (e.g., clean air and water, habitat, and biodiversity) and which ecosystems are the most vulnerable to changes?
B. What is the radiative forcing of wildfire globally accounting for greenhouse gas and aerosol emissions, post-fire recovery, and changes in surface albedo?
C. How do fuel type, structure, amount, and condition influence fire?
D. How do these smoke emission influence atmospheric dynamics and health and air quality as they are globally transported?

Answering these questions will improve understanding of fire in the Earth system, and will require continued and improved coverage of observations of ecosystems pre- and post-fire. To address these questions, the following science and application targets (“objectives”):

1. Monitoring post-fire recovery using ecosystem composition and 3-D structure
2. Mapping vegetation carbon and nitrogen
3. Mapping ecosystem condition: soil moisture and vegetation productivity, moisture, stress and mortality
4. Mapping fire emissions and smoke transport

require global observations with frequent revisit to capture before and after disturbance conditions.

To accomplish these objectives, it is imperative for continuity of observations not only to provide long-term analyses of fire’s role in the Earth system, but also to sustain integration into operational decision support systems.

Question 1, Part (B) – Importance of Targets to the Themes

The aforementioned objectives “cross-cut” Themes 2-4 as wildfires can be extreme events that directly affect the carbon cycle and have direct implications for applications’ science.

These objectives are important to Theme 2 because smoke emissions from fire are directly injected into the atmosphere, acting as air pollutants, altering atmospheric chemistry downwind of fire (gases and aerosols), and atmospheric thermodynamics, affecting local-to-regional weather and larger-scale climate systems (Figure 1). Fire emissions feedback to the climate system by producing cloud condensation nuclei (CCN)1-3, aerosols that directly and indirectly affect radiative forcings4-6, and altering the radiation balance (vegetation change, deposition on ice)7-10. Emissions also act as sources of pollution that are transported beyond localities and have the potential to affect global atmospheric chemistry and the hydrologic cycle11-18. Aerosols can influence the micro- and macro-physical and properties of clouds thus impacting the energy balance and the hydrological cycle. Smoke also contains limiting nutrients that provide necessary nutrients at both land and ocean interfaces19,20.

These objectives are important to Theme 3 because climate influences fire regimes21,22, which act as a catalyst expediting terrestrial ecosystem change across climatic gradients23-25 (i.e., temperate, boreal, and tropical). Thus fire has implications for biogeochemical cycles and ecosystem function (e.g., nutrient cycling), biodiversity and ecosystem health25. Specifically, mapping post-fire recovery (Objective 1) informs natural resource management as decision makers balance land use objectives such as biodiversity (which can be influenced by fire26), species protection and mitigating fire effects27. Fire influences ecosystem health28 by affecting biogeochemistry (Objective 2), specifically carbon and nitrogen29, cycles through nutrient cycling30 and ecosystem productivity31. Furthermore, ecosystem condition (Objective 3), an indicator of ecosystem health32, can influence the likelihood of fire32.

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As fire affects atmospheric thermodynamics and local-to-regional weather (Theme 2) and terrestrial ecosystems (Theme 3), these objectives are also relevant to Theme 4 as carbon cycling and energy exchange link the terrestrial, atmospheric, and hydrologic systems to influence the global climate system. Specifically, fires contribute to increasing atmospheric carbon, which can have countering feedbacks on the climate system. Fire emissions (e.g., greenhouse gases and aerosols discussed above) have made significant contributions to atmospheric carbon in relation to anthropogenic emissions, yet confounding impacts of fire necessitate representation of fire in global studies beyond simple carbon emission estimates. Specifically, although carbon is lost to the atmosphere during fire, fire plays an important role in nutrient cycling and regrowth which affects carbon uptake by the biosphere that impose constraints on how the carbon cycle responds to variations in climate. The incomplete combustion of biomass produces varying forcing agents including changed surface albedo from remaining charcoal and aerosols, which can absorb and scatter solar radiation, deposit on snow and ice to change surface albedo, and effects on cloud properties and formulation. Also affecting climate are changes in surface roughness and altered atmospheric mixing.

**Question 1, Part (C) – Advancing Themes by addressing Targets**

The aforementioned objectives can advance Themes 2-4 as follows.

- Terrestrial ecosystems will be better characterized (vegetation composition and vertical and horizontal structure) before and after fire, thus improving understanding of ecosystems (in their current state) and how they relate to current bioclimatic conditions, which can improve benchmarking for predicting changes. The current earth observations with limited resolutions and extent are not sufficient to resolve these relationships beyond the current state of knowledge.

- Improved understanding of terrestrial ecosystems, has the potential to resolve the varying functional role of fire and how that relates to biodiversity and ecosystem health (e.g., water quality). Mapping vegetation composition, structure and amount (e.g., biomass) are essential to characterizing habitats for protected species, resolving models of erosion, hydrologic runoff, and water quality, informing predictive models of landslide potential, quantifying emissions that degrade air quality, and predicting fire behavior.

- Current practices for fire emission estimation use models and emission factors to infer transition of biogeochemical cycles (e.g., carbon) between the biosphere and atmosphere. However, continuing observations of forest structure (e.g., NISAR, GEDI and BIOMASS) and improved mapping of ecosystem composition (e.g. image spectroscopy outperforms broadband sensors), can refine estimates of above ground biomass before and after fire.

- Increased knowledge of structure and composition (species, age) can improve estimates of aboveground biomass, while mapping ecosystem condition can provide estimates of the total available carbon for burning, particularly in ecosystems with high belowground carbon reserves that are released during burning. Thus, such observations can refine emissions estimates and combustion efficiency useful for understanding plume injection height and smoke transport.

- Mapping post-fire recovery will resolve uncertainty to local (with respect to the fire) changes in surface albedo, while improved mapping of carbon before and after can inform emissions modeling and thus resolve uncertainty in regional and global effects of black carbon and changed snow and ice albedo from deposition.
Question 2 – Utility of Geophysical Variables

All four objectives require sustained satellite observations of fire activity (e.g., fire occurrence, fire area, temperature, and fire radiative power (FRP)) as fires have global impacts even when occurring in remote areas. Specific to each objective, required observations include:

Objective 1 – mapping forest recovery: Vegetation composition can be represented by vegetation functional types, defined as assemblages of species by structure, physiology, and phenology that characterize ecosystem response to environmental conditions or disturbance severity. Current practice uses discrete functional types, however new technologies provide continuous characterization of optical types that increase functional type classifications and map vegetation functional diversity that can link biodiversity to ecosystems functions. Vegetation structure requires observations of mean and variation of canopy height, canopy base height, stem density, stem volume, basal area, and fractional canopy cover.

Objective 2 – mapping carbon and nitrogen: Mapping canopy chemical composition identifies the occurrence and the percentage composition of each in the canopy, while mapping canopy fuel load using aboveground biomass and leaf area index is essential for refining estimates of fire carbon fluxes, and pre- and post- carbon and nitrogen stocks.

Objective 3 – mapping ecosystem condition: There are many characteristics of ecosystem condition including:

- Discrimination between live, senescent/schorched, and charred vegetation can inform the health of the ecosystem (i.e., burn fraction – which performs equally as well as, but with advantages over, historically used indices of burn severity).
- There is a range of proxies to characterize vegetation stress, a critical observation for understanding how flammable an ecosystem is, including observations of precipitation, temperature, relative humidity, wind speed and direction, soil moisture, soil temperature, vegetation water content or equivalent water thickness.
- Ecosystem flux affects fuel accumulation (e.g., systems with rapid succession or that are water limited) and is relevant to mapping post-fire regeneration. Thus, observations are needed of gross primary productivity that can be derived from fraction of photosynthetic active radiation, leaf area index, vegetation greenness, or solar induced fluorescence.

Objective 4 – emissions and transport: knowing the fuel amount, condition, and stand age is necessary to determine the combustion completeness, injection height and the vertical profile of emissions in the atmosphere, which affect smoke transport.

Question 3 – Measurement and Observation Requirements

To observe these geophysical variables, measurements are needed contemporaneously (not simultaneously) across three payloads: (1) a thermal infrared (TIR) radiometer, (2) a Visible-Shortwave Infrared (VSWIR) imaging spectrometer, and (3) an active sensor as well as observations produced from data assimilation.

Fire detections and land surface temperature need sustained global TIR radiometric retrievals at ≤375 m pixel resolution at nadir +/- 60° with sub-daily observations and an NEdT of 0.2K and ≥9 bands at: −8.3 μm, −8.6 μm, −9.1 μm, −11 μm, −12 μm to distinguish land surface temperature (LST) from emissivity, −4 μm with ≥400 K saturation and sufficient thermal range for fire detections (but may require 2-bands to have sufficient sensitivity at the lower temperatures), −1.6 μm and −2.2 μm for cloud detection, geolocation and flagging false positives.
Vegetation functional types, gross primary productivity, and fire severity need continued coverage of multiple Landsat-like data. To advance Theme 3, a VSWIR imaging spectrometer is needed (Figure 3) with continuous spectral range 0.4-2.5 μm at ≤10 nm spectral sampling, ≤30 m pixel resolution, ≤16 day observation repeat, a 185 km swath, high signal-to-noise and global coverage that provides:

- analogous Landsat observations using spectral-response functions
- canopy chemical composition (Figure 3a) and equivalent water thickness, and
- live, senescent or scorched, and charred vegetation

Vegetation structure and aboveground biomass can be observed using full waveform or discrete return active sensors: Light Detection and Ranging (LIDAR) and single-band microwave synthetic aperture radar (SAR). Generally, full waveform improves dense canopy penetration and may improve dense vegetation structure characterization. LIDAR can be used vertically in the atmosphere to characterize plumes (e.g., CALIPSO) and horizontally to scan the Earth’s surface (e.g., GEDI, GLAS, IscSAT-1/2). However, SAR has the advantages of penetrating cloud cover, observing soil moisture and vegetation water content, and global mapping ability (as opposed to sampling). Research and management require a scene area of 75 km with nominal resolution of ~1 ha, which requires measurements at ≤20 m resolution to reduce noise, and ≥2 observations per year to resolve changes in phenology and snow contamination. A repeat-pass InSAR configuration with 2 looks are likely to result in unacceptable levels of interferometric decorrelation, thus baseline SAR observations require fully polarimetric (HH, HV, VH, VV) L-band and tandem (single pass) interferometry, while threshold SAR require a dual polarimetric L-band with cross polarization (HH, HV) and repeat-pass interferometry with ≥3 looks to reduce SAR speckle.

Data Assimilation: Meteorological data derived from the GEOS-5 data assimilation system are needed for model smoke transport, fire behavior forecast models with the realistic potential to save lives, and fire danger modeling. Research and development is needed to provide data at higher spatial (≤300 m pixel) and temporal (3 hr) resolution that accounts for regions with complex mountainous topography.

**Question 4, Part (A) – Feasibility and Affordability**

TIR Radiometer: Consistent TIR measurements are required across missions or through continued existence of these missions. It is assumed measurements from MODIS and VIIRS will continue through the NPOESS and JPSS programs; however, in order to advance fire information products from TIR, new global mapping satellites must consider instrument development that increases the saturation temperature while providing sub-daily data with ≤375 m pixel resolution. Although there is a trade in spatial and temporal resolution, a new TIR platform meeting this spatial requirement could augment the frequency of TIR observations from VIIRS and MODIS while providing a spatial resolution for LST observations, which are needed to assess vegetation stress.

NASA-guided engineering studies (2014,2015) demonstrated the feasibility of a 3-year, Class C mission with TIR radiometer at 60 m pixel resolution, 1200K saturation, and 2-day temporal repeat at the equator. This radiometer would fit with a size, weight and power (SWaP) compatible with a Pegasus class launch (Figure 4) and would use key technologies developed from previous investments (e.g., TIMS, PMIRR, MASTER, TES, MCS/DIVINER, HyTES and PHyTIR, and ECOSTRESSSS) including the focal plane, cryocoolers and scan mirror assembly (Figure 5). Data rate and volume have been addressed using readily available onboard solid state recorded (SSR) and algorithms for lossless compression and real-time cloud screening processes, thus enabling Ka band downlink of all terrestrial measurements.
**VSWIR Imaging Spectrometer:** Providing the needed measurements from an imaging spectrometer requires a different sensor than has been used on Landsat, however it builds on a legacy of previous investments in response to the 2007 NRC Decadal Survey\(^{92}\) and the 2013 NRC sustainable land imaging report\(^{68}\). AIS\(^{93}\), AVIRIS\(^{94}\), AVIRIS-NG\(^{95}\), NIMS\(^{96}\), VIMS\(^{97}\), Deep Impact\(^{98}\), CRISM\(^{99}\), EO-1 Hyperion\(^{100,101}\), M3\(^{102}\), MISE, and the IS now being developed for NASA’s Europa mission.

NASA-guided engineering studies (2014, 2015) showed that the needed imaging spectrometer (Section 4a) can be implemented as a 3-yr class C mission (in comparison to the Class B Landsat missions) with SWaP compatible and a Pegasus class launch (Figure 6). Key to the design is an optically fast spectrometer\(^{103}\), for which a scalable prototype F/1.8\(^{104}\) has been developed, aligned, and qualified (Figure 5). Data rate and volume have been addressed using a lossless compression algorithm\(^{87-89}\) and a real-time cloud screening process\(^{91}\), thus enabling Ka band downlink of all terrestrial measurements (Figure 7). Algorithms for automated calibration\(^{94}\) and atmospheric correction\(^{105,106}\) are operational. International partnerships may enhance affordability.

**Active Sensor:** Many existing and future satellites (Section 4b) prove feasibility and affordability for collecting measurements characterizing the Earth’s surface from active sensors; however, more research is needed to translate algorithms to bridge observations across satellite platforms. **Consistent active sensor measurements and respective observations are required across missions or through continued existence of these missions.**

For characterizing emissions and accurately quantifying smoke transport to remote locations, a vertical LIDAR is needed. The successes of the CALIOPE instrument on CALIPSO demonstrate feasibility and affordability for space-based measurements. Future flight projects may consider airborne (e.g., multi-wavelength High Spectral Resolution Lidar (HSRL-2)) campaigns to target specific events and address smoke transport questions relevant for management and research teams.

**Question 4, Part (B) – Synergistic Measurements**

Current and planned thermal sensors that provide data information products relevant to fire include MODIS, VIIRS, and ECOSTRESS. MODIS and VIIRS provide very similar products (burned area, fire detection, and FRP), however they are distinct missions and research is needed to bridge the datasets to provide data products available through one record. In 2018, the 1-yr ECOSTRESS mission will provide a base map of vegetation water-use efficiency in sub-regions around the world that will be invaluable to assessing ecosystem stress in relation to pre- and post-fire ecology.

Current and future satellites that complement a VSWIR imaging spectrometer with global mapping ability include those from the Landsat constellation (Landsat and ESA’s Sentinelle 2/3), which provides frequent observations useful for immediate response to fire. Longer-term management and investigations of fire in relation to terrestrial ecosystems, however, will require more information than can be derived from broadband data\(^{107}\). The future DLR hyperspectral pointing instrument EnMAP\(^{108}\), expected to launch in 2018 and operate for 5 years, and JAXA’s ALOS-3 with an imaging spectrometer HISUI and broadband sensor\(^{109}\) can facilitate ongoing research to improve regional processing of geophysical variables that are both backwards compatible with broadband sensors\(^{66-68}\) and utilize the full breadth of information available in hyperspectral data.

While there are many existing and planned synergistic active sensors (NASA’s IceSAT-2\(^{110,111}\), GEDI\(^{112}\), SMAP\(^{113-115}\), CALIPSO\(^{116}\), NASA-ISRO’s NISAR\(^{117}\), and ESA’s BIOMASS\(^{118}\) and Sentinelle 1\(^{119}\)), the fire community needs a continuous record across decadal time scales, thus consistent production of information products either between missions or through continued existence is essential.
**Figures**

*Figure 1.* A schematic of the role of fire in the earth system. Figure modified from Ward et al. (2012).
Figure 2. The number of independent components that can be classified by spectral data depends on the number of spectral bands and the spectral resolution of the data. Underlying spectral features are often broader than a single spectral band and many plant constituents have spectral features across the spectrum, thus there are many fewer independent components than there are spectral bands\textsuperscript{107}. This figure is reproduced from Scime et al. (2013)\textsuperscript{107}.

Figure 3. Comparing imaging spectroscopy to broadband where (a) depicts the contiguous spectral coverage over several key endmembers for fire science from VSWIR Dyson, which shows much more detail of optical traits of each endmember (e.g., lignen and sugar content) compared to (b) broadband sensor Landsat. (c) Demonstrates the different signal-to-noise (SNR) ratios by sensor. In order to compare SNR, the contiguous spectra from VSWIR Dyson were back-transformed into equivalent bands as the broadband sensors using spectral response functions\textsuperscript{66–68} to convolve the spectra\textsuperscript{107}. Figure 3c is reproduced from Mouroulis et al. (2016)\textsuperscript{103}.
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Figure 4. (left) Opto-mechanical configuration for a wide swath, high resolution TIR imaging radiometer system providing 73-degree swath and 60 m sampling. TIR Imaging radiometer with spacecraft (265 kg, 187 W) configured for launch in a Pegasus shroud for an orbit of 410 km altitude, 97.07 inclination to provide 2-day revisit for three years. (right) Orbital altitude and repeat options. An altitude of 410 km with a fueled spacecraft supports the three-year mission with the affordable Pegasus launch. Higher orbits require a larger launch vehicle.

Figure 5. (left) Design of ECOSTRESS TIR Push-whisk scanning system covering a wide field of view with an 8 band SWIR to TIR sensor. (right) Developed, aligned and qualified PHyTIR push-whisk system with TIR full range multi-band detector array.

Figure 6. (left) Opto-mechanical configuration for a high SNR F/1.8 VSWIR imaging spectrometer system providing 185 km swath and 30 m sampling. (center) Imaging spectrometer with spacecraft (265 kg, 134 W)
configured for launch in a Pegasus shroud for an orbit of 429 km altitude, 97.14 inclination to provide 16 day revisit for three years. (right) Orbital altitude and repeat options. An altitude of 429 km with a fueled spacecraft supports the three-year mission with the affordable Pegasus launch. Higher orbits require a larger launch vehicle.

Figure 7. Design of F/1.8 VSWIR Dyson covering the spectral range from 380 to 2510. (right) Developed, aligned and qualified Dyson with CHROMA full range VSWIR detector array.

Figure 8. (left) Global illuminated surface coverage every 16 days. (right) On-board data storage usage for illuminated terrestrial/coastal regions with downlink using Ka Band to KSAT Svalbard and Troll stations. Oceans and ice sheets can be spatially averaged for downlink.
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