The Need for Full 3-D Characterization of Global Ecosystems

2017-2027 NRC Decadal Survey in Earth Science and Applications from Space

1. **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?**

An overarching question for the NASA science mission is "How is the Earth changing and what are the consequences for life on Earth?" Four key related questions were posed at a recent workshop on Terrestrial Ecology, Carbon, Land Cover and Biodiversity: 1. How long can Earth's ecosystems sustain their functions as they are modified by climate and human activities? 2. How will water and food security be affected as climate changes and human consumption intensifies; how will they respond to various policies aimed at adapting to and mitigating these effects? 3. What are the consequences of significant changes to existing ecosystem services? 4. Biodiversity and ecosystem sustainability are changing as a result of human alterations to the landscape. What are the consequences for human well-being? The answers are to be found by quantitative understanding and characterization of Earth' s biosphere which leads to accurate models of ecosystem dynamics. During the past 18 months members of the land science communities have worked together to describe and prioritize measurements required to support research objectives of these communities. In addition, notional technical approaches (field, suborbital and orbital) and frameworks to acquire the needed measurements were identified. Several key scientists participated in a workshop and recently released a report on the findings. Prominent among the findings of the workshop report (i.e., Goetz and Hall, 2015 and related white paper submission) is the need for high definition ecosystem structure information:

> "The ability to map ecosystem structure with greater certainty will in turn lead to more certain estimates of ecosystem functions (photosynthesis, respiration, transpiration) as they relate to structure. Lidar collections provide the cutting-edge structural details that can contribute to better maps of ecosystem composition, especially in concert with the differentiating spectral information provided by imaging spectrometry. Image time series can contribute the best available synoptic information regarding vegetation phenologies, providing yet further information for characterizing composition, as well as function. Radar is helpful for mapping ecosystem structure at larger scales than can be currently characterized synoptically with lidar. "

The latest IPCC Assessment Report (2014) report noted there is high confidence that carbon stored (i.e., biomass) in the terrestrial biosphere is susceptible to loss to the atmosphere as a result of climate change, deforestation, and ecosystem degradation. Another workshop on Carbon and Climate (Schimel et al., 2015) focused on large scale modeling and stated biomass ((a component of vegetation structure) measurements provide a long-term integral constraint on land carbon fluxes and repeated measurements of biomass provide a decadal scale constraint on land-atmosphere models. The report pointed out that contemporary missions such as ALOS-

PALSAR and planned missions like GEDI, BIOMASS, and NISAR) may provide measurements of carbon stocks in the current era. The aforementioned systems should do a credible job of estimating the state of global biomass. The purpose of this white paper is to advocate for detailed understanding of ecosystem structure and functions that require measurements not captured by these missions.

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

A high priority measurement need identified by all carbon cycle discipline groups was the missing hi-resolution vertical dimension of vegetation and surface structures. According to the Schimel et al. report the vertical information component could be acquired from lidar and radar (e.g. GEDI, IceSat-2, NISAR and BIOMASS missions that are already planned for this decade). This is true when considering canopy height as the driving variable for biomass estimation, however, measurements from these systems do not provide sufficient details of surface and canopy structures. These planned missions are an attempt to address key issues regarding forest biomass as called for in the first Earth Sciences Decadal survey and should provide for the first time global higher resolution (10s of meters) observations that can be used to estimate forest biomass based on estimates of lidar derived heights or scattering phase center heights. The planned measurements may either be spatially discontinuous, lack global coverage, or lack spatial detail.

Key challenges for acquiring necessary three-dimensional structure information of vegetated ecosystems include detailed vertical knowledge along with temporal and spatial coverage. What is critically needed in the next decade is detailed contiguous along and across track observations of canopy structure., i.e. 3-D swath maps. Accurate and high-resolution measurements of 3D structure are critical for knowledge of above ground and below ground carbon in forests (e.g., Naessett and Gobakken 2008)). In addition detailed and high-density 3D measurements provide information of ecosystem structure that can be applied to the understanding of impacts on biodiversity from natural and anthropogenic sources (Bergen et al. 2009). For example, subtle but extensive changes such as permafrost thaw could impact traditional food and shelter resources for animals and humans across the Arctic zone. Changes in ecosystem structure from establishment of new species in formerly unsuitable habitats can impact ecosystem health and services. Disturbance frequency and impact may increase in the face of climate change, as may the frequency and severity of natural hazards. Sampling biomass, as mentioned above, helps the understanding of the state of carbon, and 3-D mapping of carbon will provide insight into the fate of carbon in vegetation and the consequences for other life forms including humans.

Annual measurements of the three-dimensional structure of vegetation at meter scale horizontal resolution and sub-meter vertical resolution are required to characterize and quantify change in ecosystem structure and the implications for carbon balance, biodiversity and ecosystem structure. Technologies exist now to acquire these measurements. For example, new US government policies are making commercial high resolution (i.e., sub-meter) stereo imagery available to scientists and detailed structure information is being gained (e.g., Neigh et al, 2013, Montesano et al 2105). These types of measurements have shown promise for characterizing forest canopy height models but lack accurate surface elevation vertical canopy. Spatial and temporal acquisition strategies limit the usefulness of these data for detailed ecosystem dynamics studies.. A combination of contiguous, repeatable high-resolution stereo-imagery with contemporary high density lidar retrievals provides a tractable approach.

We envision a system that can characterize the 3-D structure of vegetated ecosystems with ground swath of 10s of kilometers supported by detailed and contiguous vertical vegetation structure and ground elevation measurements. This imaging/structural solution should provide swath coverage of high resolution (sub-meter), have carefully chosen multispectral bands, and of course be well-calibrated. An imbedded array of high resolution vertical structure measurements (e.g.multicolor, waveform or high repetition rate photon counting lidar) would provide contemporary detailed structure and surface elevation measurements not obtained by the imaging system. Repeated swath measurements frequent enough to capture important phenological or growth stages that can be used to assess productivity and viability within regions undergoing rapid change are also required. The mutispectral bands of interest include those necessary for vegetation density, composition and productivity. Vertical profile measurements that capture complete (i.e., ground to canopy top) structure should be measured contiguously along track at high resolution (~1m). These data will provide further insights into the full 3D structure, composition and functioning of vegetation that can fused with the larger swath instrument data. Multiple across-track footprints would be especially useful in this context. This would be especially valuable at orbit crossover points and will provide highly detailed maps of ecosystem change.

The complete data set will offer powerful synergies with other remote sensing and *in situ* observations. For example, coincident observation of swaths by optical instruments such as Landsat or instruments that are sensitive to photosynthetic rates (e.g., ESA FLEX, NASA OCO-2) can benefit from detailed characterization of the surface. The data would provide excellent forest characterization and biomass estimates that can used for science product validation with any number of missions planned to estimate biomass over large areas (e.g., GEDI, ICESat 2, BIOMASS, NISAR and their follow-on missions). The swath approach would also be useful for missions requiring accurate surface topography including non-vegetated areas such as glaciers, deserts and coastal ecosystems such as salt marshes, mangroves, dunes and tidal flats.

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

Terrestrial ecosystems change in response to natural and anthropogenic forcing. This planet-wide phenomenon that affects life on Earth from local to global scales and must be measured repeatedly from space. Airborne systems can provide excellent calibration and validation measurements and have been shown to be useful for "filling in" missing data (.e.g., ICEBridge). Schimel (2015) noted that a five- to ten-year cycle of repeat measurements are needed at all latitudes, and could monitor disturbance and land-use impacts and provide information about the response of terrestrial biomass to climate change and increasing atmospheric CO_2. The proposed measurements can contribute to information while providing new insights into ecosystem structure and function. The measurements discussed herein (high-resolution, multispectral, full 3D structure, well-calibrated image data fused with contiguous samples of high spatial resolution vegetation structure) are not being produced by current or planned Earth observing sensors. Commercial high resolution satellite imagery, GEDI lidar and known SAR missions do not provide coincident, temporal frequency, spectral coverage or consistent resolution necessary to monitor ecosystem dynamics in the face of climate change. The measurement suite represents a sea-change from wall-wall 2-D land attributes mapping to contiguous sampling of the #-D structure, function and composition of the Earth's biomes.

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