Terrestrial Ecology, Carbon Cycle, Land Use / Land Cover Change, and Biodiversity (TECLUB)

Priority Science Questions and Measurements

1.0 Summary of Workshop Outcomes

1.1 Objectives

The objectives of the TECLUB workshop were to (1) engage the relevant terrestrial ecology, carbon cycle, land use / land cover change and biodiversity science communities to describe and prioritize measurements required to support research objectives of these communities (2) identify notional technical approaches (field, suborbital and orbital) and frameworks to acquire the needed measurements and (3) produce a white paper useful for science practitioners and science policy communities, including the 2015 Decadal Survey panel(s), articulating the outcomes of the TECLUB deliberations.

1.2 Rationale

The workshop objectives support those articulated in the 2010 NASA Earth science plan, "How is the Earth changing and what are the consequences for life on Earth?" NASA seeks to characterize, understand and predict the current and future state of global Earth systems by addressing three critical science questions; (1) How is the global Earth system changing? (2) What are the sources of change in the Earth system and their magnitudes and trends? (3) How will the Earth system change in the future?

NASA relies on the Earth science community to identify and prioritize leading-edge scientific questions and the observations required to answer them. One principal means by which NASA's Science Mission Directorate engages the science community in this task is through the National Research Council (NRC). The NRC conducts studies that provide a science community consensus on key questions posed by NASA and other U.S. Government agencies. For the next decadal survey NASA and its partners ask the NRC to look out ten or more years and prioritize research areas and observations most needed to meet NASA's objectives. The last NRC Report, the Decadal Survey Report, was released 15 January 2007. NASA responded positively to its recommendations and began implementing many of them after the survey's release. In 2014 the NRC undertook a "mid-term assessment" of NASA's progress and is now preparing to undertake the next Decadal Survey to establish recommendations for NASA's Earth Science Program for 2020 and beyond.

1.3 Approach

A two and one-half day workshop was held at the Goddard Space Flight Center beginning 28 October 2014. Three discipline teams and one measurement team were formed from the research community; a Carbon Cycle science (CC) team, a Land Use Land Cover Change (LC) team, a Terrestrial Ecology / Biodiversity (TE / BD) team, and a measurements (MMT) team. The MMT team was integrated with the three discipline teams, with the intent of addressing the nominal measurement requirements specified by the discipline teams. On the first two days of the workshop there were team breakouts in the mornings and afternoons interspersed by plenary report-back sessions. One measurement team breakout was held following three discipline breakouts to integrate and summarize the requirements from the discipline teams.

The final half-day was devoted to prioritizing the integrated measurement needs across all disciplines, developing writing assignments, and schedules for completion of the report. Team breakouts were organized to ensure that teams addressed sequentially (1) the most important societal issues, (2) science questions, (3) analysis frameworks and (4) measurement needs (Figure 1.1). This approach ensured that measurement needs were linked in a traceable way to societal issues.

The topics were addressed in the context of existing data records and measurement technology (satellite, aircraft and ground) and feasible future technology and measurement approaches to acquire and manage the data collections.

The workshop management team consisted of Dr. Forrest Hall of the University of Maryland/Goddard Space Flight Center Joint Center for Earth Systems Technology and Dr. Scott Goetz of the Woods Hole Research Center. They selected, in collaboration with the NASA program managers, a core workshop panel to lead the overall effort consisting of about 20 scientists from a range of Earth science research institutions as well as government agencies including NASA, USGS, USFS, NSF, NOAA and the DOE. In addition, the workshop was open to an additional 30 team members representing expertise across the Earth science community, who confirmed or expressed a desire to participate. A website documenting all workshop deliberations will be established for anyone who wishes to submit their ideas or to comment.

Prior to the workshop a series of teleconferences was held to discuss the workshop approach, and the overall scope, approach and structure of the report ("white paper"). The core team produced a first draft in the form of presentation outlines focusing on data requirements to be discussed at the workshop.

The workshop relied on many previous studies defining data needs, including those arising from the previous NRC decadal survey study, the mission design efforts that flowed from those, and recent workshop reports such as the CEOS Strategy for Carbon Observations from Space (CEOS 2014).

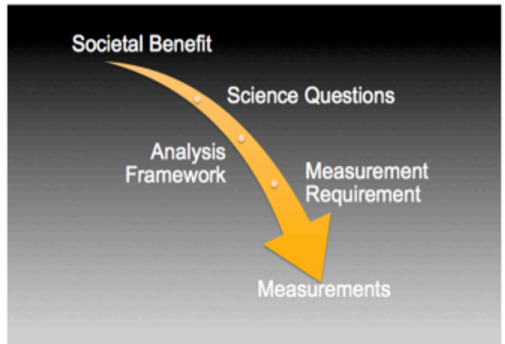
This report contains 3 chapters. This, the first chapter, summarizes how discipline and measurement scientists organized and established the measurement requirements that resulted from two and a half days of deliberation. Chapter 2 contains the individual discipline workshop reports. Section 2.1 contains the biodiversity/terrestrial ecology working group report, Section 2.2 the land use land cover change report, and Section 2.3 the carbon cycle working group report. Chapter 3 reports the integrated measurement requirements from all discipline groups and then describes how those requirements could be met using existing remote sensing technology, as well as which new technologies might feasibly be implementable in the next decade.

1.4 Societal Benefit Context for Science Questions

The Earth is a "complex changing planet" on which the climate and ecosystems are changing rapidly, driven by society's accelerating use of the Earth's natural resources. These changes are increasingly the concern of policy makers, as societally important functions become increasingly impacted by these changes. From climate change, to carbon management, to biodiversity protection, to food security, and other key issues, both policy and the science needed to support policy are on the rise. Given the gravity of changes taking place, the societal benefit context provides an important way to prioritize potential science questions, and their associated analytical frameworks and measurement requirements amenable to satellite remote sensing.

Societal Relevance

Understanding the complex, changing planet on which we live, how it supports life, and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing humanity. It is also one of the most important challenges for society as it seeks to achieve prosperity, health, and sustainability.... NRC2007



Measurement Needs

Understanding changes and their implications requires a foundation of integrated observations taken from land, sea, air, and space based platforms – on which to build credible information products, forecast models, and other tools for making informed decisions. NRC 2007

Figure 1.1 Organization of data and measurement requirements in the context of societal benefits and information needs, science questions that must be addressed to provide the necessary information, the analysis framework required to address the science questions, and the measurements needed as input and validation.

The Global Earth Observation System of Systems (GEOSS) identified nine societal benefit areas (SBAs) including: disasters, health, energy, climate, water, weather, ecosystems, agriculture, and biodiversity. The previous NRC2007 report identified three science themes: disruption of the carbon water and N cycles, Changing land and marine resource use, and changes in disturbance cycles. Most recently, Working Group III from the recent IPCC-AR5 report identified four key "knowledge gaps" including: improved global high‐resolution data sets of crop production systems, globally standardized and homogenized data on soil as well as forest degradation, improved understanding of land based climate mitigation options, and better understanding of the effects of climate change on terrestrial ecosystem productivity and carbon stocks. And, the U.S. Congress directed NASA toward the development of a prototype Carbon Monitoring System (CMS) to provide transparent data products that achieve the accuracy required by current carbon trading protocols and national-scale reporting and monitoring efforts.

Intelligent policy decisions within these domains demand answers to many unanswered questions. How long can the Earth's vital ecosystems sustain life as climate and humans modify them? The productivity of agricultural ecosystems is climate sensitive. How will water and food security be affected in the future as climate changes and human consumption intensifies; how will they respond to various policies aimed at adapting to and mitigating these effects? What are the human consequences of reduced ecosystem services? Terrestrial and marine ecosystems serve to slow the rate of climate change, absorbing half of society's fossil fuel emissions. But the ecological processes and uncertainties underlying net uptake of carbon in terrestrial ecosystems are less understood than in marine ecosystems. Which terrestrial ecosystems are most responsible, and by how much? How are climate and anthropogenic changes affecting their ability to take up carbon? Most importantly, it cannot be forgotten that terrestrial ecosystems sustain all terrestrial organisms. Biodiversity and ecosystem sustainability are declining rapidly as a result of human alterations to the landscape, with poorly understood yet likely enormous consequences for human well-being.

To address needs in these areas, this report is organized into three broad categories: terrestrial ecology & biodiversity, land use & land cover change, and carbon cycle science. Measurements are identified in each of these areas to monitor changes in important variables with sufficient accuracy to serve as input to analysis frameworks and models to inform understanding, attribution, and prediction.

1.5 Measurement Requirements and Priorities across Scales

The TECLUB discipline groups developed a consensus vision for the next decade that considered not only global and regional measurement needs, but also the analysis framework research needed to translate those measurements into the answers and information required to address a broad array of societal issues and science questions.

In contrast to deliberations of the 2007 Earth Science Decadal Survey, the TECLUB workshop organized its discussions around measurement needs, not mission concepts. However it was recognized that global measurement needs can only be addressed by orbital missions, while for regional measurements, suborbital venture class missions would likely be the most cost effective approach. Some measurement requirements can only be met using *in-situ* measurements from field networks. The TECLUB measurements group, composed of discipline scientists and technologists provided guidance as to the technological feasibility of acquiring the needed orbital, suborbital and field measurement by considering the TECLUB integrated measurement needs together with possible technology approaches to acquiring the required data.

As will be seen, TECLUB measurement needs identified for the next decade will require maintaining legacy capabilities in order to extend the multi-decade 30 m resolution data records well into the future; but also will require an increase in satellite overpass frequencies from ~bi-monthly to sub-weekly to ensure cloud-free data every week over the global land surface.

The traditional two-dimensional data records will need to be augmented with measurements of vegetation's vertical dimension, crucial to complete the picture of vegetation structure and its interaction with the environment.

Another dimension, hyperspectral (i.e. imaging spectroscopy) global observations, will also be needed to quantify photosynthetic rates and vegetation condition. Because vegetation receives illumination from the entire upper hemisphere under a wide range of illumination angles, a near instantaneous, multi-angle multi-spectral view of vegetation will help to quantify highly variable photosynthesis rates.

The TECLUB discipline teams recognized that while all these measurements are urgently needed to address the science questions and policy information needs for the next decade, they also recognized that developing and flying the necessary instruments will take time; hence the discipline groups discussed, and agreed upon a consensus prioritization of TECLUB data needs, providing the implementing agencies a suggested time line for bringing these new technologies on line.

To address the compelling questions summarized above, the science community must better understand and quantify the state and dynamics of terrestrial ecosystems. The conclusions of this community's workshop deliberations were that to meet this challenge, it will need (1) continuity in the current global observational data and capabilities already in place, (2) improved temporal frequency, spectral and spatial resolution of those observations and (3) new kinds of observations now available using remote sensing technologies and approaches developed in the last decade.

The TECLUB measurement requirements are organized herein by global and regional spatial extents. Global requirements can only be addressed with orbital missions, but are required to satisfy the most pressing information needs articulated by policy makers in order to mitigate the impacts of climate change and land use – land cover change on human societies, agricultural security, and faunal and floral biological diversity. Regional and local data requirements, which can be addressed from sub-orbital missions (aircraft, drones, balloons etc), focus on developing the information necessary to permit policy makers to assess and mitigate regional impacts in arctic, boreal, temperate and tropical ecosystems, as well as regional field studies to acquire the data necessary to assess and validate the remote sensing algorithms and analysis frameworks needed to generate the required information. In the longer term, these regional data requirements must also be satisfied globally.

The priority global and regional data requirements are briefly summarized here, then articulated in more detail and justified in terms of societal needs, science questions, and analysis framework requirements in the discipline sections that follow.

1.5.1 Measurement priority #1

The first measurement priority for all disciplines emerging from the workshop was to increase the observational frequency of the legacy 30m spatial resolution data to acquire ~ weekly observations.

Weekly cloud free observations will permit finer temporal scale resolution of vegetation composition, vegetation function and condition. These data were identified as essential by the land cover – land use change group to enable detection, quantification and characterization of rapidly changing land use surfaces (Whitcraft et al. 2015). Frequent repeat moderate resolution data were also identified as important by the terrestrial ecology / biodiversity group for characterizing phenology (phenophases), identifying taxonomic diversity, and capturing dynamics in persistently cloudy areas of the tropics. The carbon cycle group also identified frequent temporal resolution data as essential for some of these same reasons: capturing phenological dynamics, rapid land use transitions, and linking modeling results to continuously operating flux measurements. Cloud-free, spatially explicit spectral observations at ~weekly intervals require a 3 to 4 day repeat overpass to achieve weekly cloud free observations globally, but particularly in regions characterized by high cloud cover.

As shown in Figure 1.2, the ability to accurately discriminate among natural and agricultural land cover types depends not only on spectral data (illustrated here by EVI or NDVI), but also on multi-date spectral data to take advantage of the different seasonal growth habits of land cover types. While multi-spectral platforms like Landsat, SPOT and Sentinel must remain to provide a long-term record of top-level land cover categories (range and croplands, forests, etc.), more frequent observations are needed to distinguish among more crop types and forest species. Cloud-free observations from legacy satellites are too infrequent to resolve key vegetation phenological differences (Figure 1.2a). A number of studies have indicated that weekly cloud-free observations would significantly improve land cover discrimination (e.g., Wardlow et al., 2007) and analyses using cloud cover statistics show that satellite revisit times of 3 to 4 days are necessary to permit weekly cloud-free observations (Figure 1.2b).

The spectral and spatial data to satisfy these measurement requirements could be achieved by augmenting the existing constellation of existing and planned US, European, Japanese, Brazilian and other satellites with space missions to increase the frequency of cloud-free acquisitions to weekly from the current 14-day or greater frequency of low-earth orbit, multi-spectral imagers. The higher temporal resolution would enable significantly enhanced vegetation structure, function and dynamics information by exploiting multi-date phenological information (Yan and Roy, 2014, Elmore et al., 2012, Roy et al., 2010), and much-improved land cover type discrimination (particularly for global agriculture mapping and monitoring). Adding capacity to acquire selected high spectral resolution data would provide essential information on vegetation condition (i.e. structure, function, and health) at critical time steps. In all disciplines represented in this report, better coordination between sensors and derived data products across international space agencies are needed to improve the spatial and temporal resolution of land change dynamics through the use of virtual satellite constellations. Other major requirements include the continuation of the 40 year Landsat record.

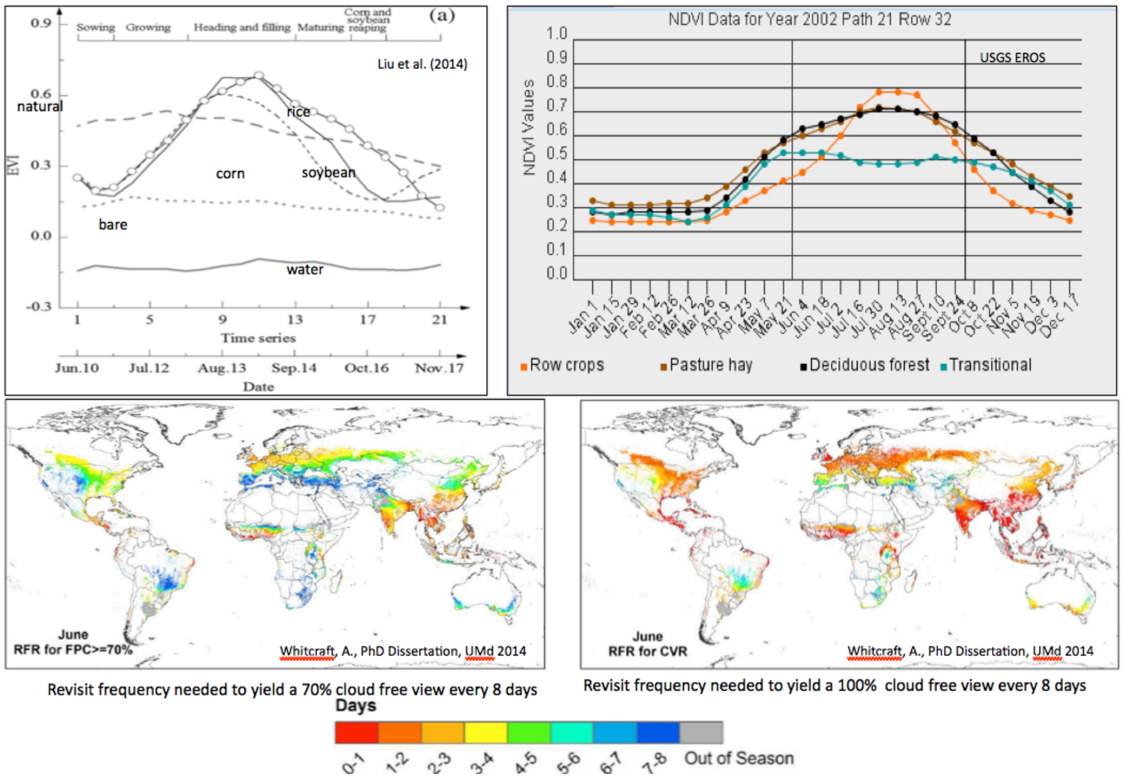


Figure 1.2: (a) Weekly cloud free observations are required to adequately sample vegetation phenology for accurately distinguishing among land cover and crop types. (b) In key cropping and forested regions, 3 to 4-day satellite revisit frequencies are necessary to ensure weekly 70% cloud-free observations. 1 to 2 day revisits would ensure 100% cloud free observations. Figure from Whitcraft et al. 2015.

We note that measurement needs were addressed independently of the status of remote sensing technology. For example, the first priority measurement need for more frequent acquisitions recognized these may become available from planned missions. For example, launch of ESA's Sentinel 2 satellites in 2015 and 2016 and a functioning Landsat 8 should provide 3 to 4 day repeat in most Landsat bands. If this comes to pass, then TECLUB first priority will have been met and then the second priority moves to first.

1.5.2 Measurement priority #2

The second priority measurement need identified by all discipline groups was the vertical dimension of vegetation structure.

It is critical to add the vertical information to the two dimensional, 30m resolution dynamic maps of vegetation community composition. At a minimum, annual measurements of the three-dimensional structure of vegetation at meter scale horizontal resolution and sub-meter vertical resolution are required to enable enhanced characterization and quantification of land use and land cover change, and to quantify forest biomass for global carbon cycle and terrestrial ecosystem studies, as well as habitat for better understanding biodiversity (Figure 1.3).

Again, TECLUB measurement priorities reflect needs rather than the status of planned missions or technology readiness. The vertical information component could be acquired from a combination of lidar and radar (e.g. the GEDI, IceSat-2, NI-SAR and BIOMASS missions already planned for the next decade) but that does not reduce the urgency with which such data are needed.

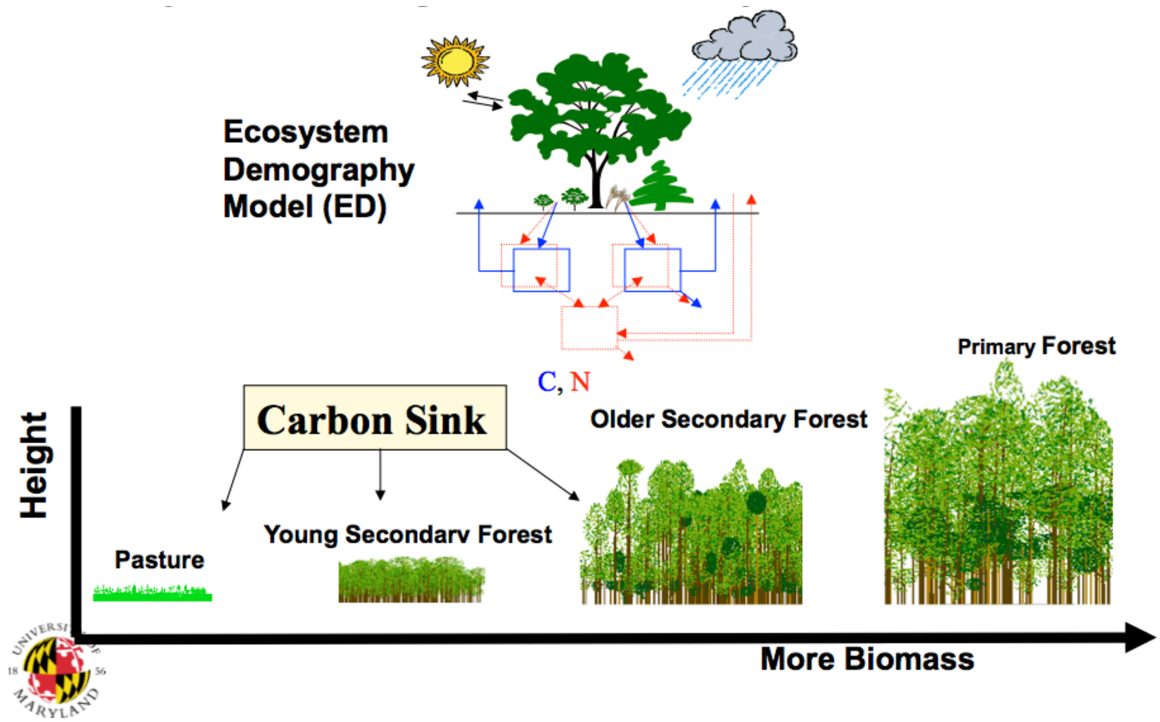


Figure 1.3: Lidar, InSAR and Radar measurements of the vertical forest dimension can provide biomass stocks and change information relevant to the Earth's biogeochemical cycles, and biodiversity habitat.

1.5.3 Measurement priority #3

The third priority is quantification of primary productivity and agricultural yields of food and fiber through improved measurements of vegetation and biogeochemical composition, function, photosynthetic capacity and rates.

Such data sets could be acquired by augmenting the Landsat and Sentinal 2 weekly cloud free multispectral imagery at ~30 m spatial resolution. This would require an additional satellite carrying an imaging spectrometer with appropriately selected narrow spectral bands spanning the vegetation chlorophyll-a to thermal spectral domains. The additional bands are desired to quantify the biochemical status of vegetation, photosynthetic capacity and rates of surface-atmosphere carbon, water and energy exchange. These data could of course also be acquired using a full spectrum imager to provide additional spectral flexibility. Trade studies to quantify the added value of full spectrum imaging over selected narrow-band imagers in terms of their relative operational complexity, data handling and cost will need to be conducted to determine the best approach.

Multi-angle imaging of the landscape using selected narrow spectral band imagers or full spectrum imaging can provide critical additional information to quantify the components of gross primary production (PAR, Fpar and Light Use Efficiency) and fluorescence emissions related to these variables.

The satellite capability to monitor the global carbon cycle is lacking in comparison to satellite monitoring of the global water and energy cycles. Monitoring the global terrestrial carbon cycle is the missing key to achieve scientific understanding of climate feedbacks and prediction of climate scenarios. To date, terrestrial carbon feedbacks are the single most critical factor limiting the accuracy of those predictions. This lack of spatially and temporally comprehensive information results in a wide range of estimates (Friedlingstein et al. 2014), and model uncertainties are large, on the order of about ±40%. To improve upon these uncertainties, a synergistic measurement framework is needed with specific data requirements at local, regional and global scales (Figure 1.4).

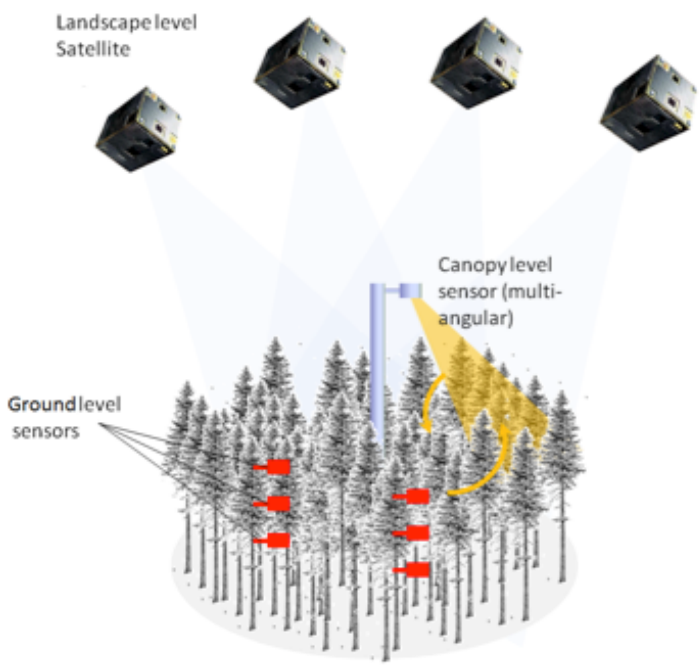


Figure 1.4 An added dimension, simultaneous *hyperspectral* or *multi-angle, selected narrow-band* global observations of photochemical indicators of photosynthetic rates could quantify photosynthetic rates and vegetation condition. Field measurement networks will be needed to validate these capabilities.

1.5.4 Regional Data Requirements.

The top priority for regional data include high resolution imagery for validating and understanding medium resolution measurements of LULCC and ecosystem function, as well as accurate, dense atmospheric carbon concentration measurements over key regions, particularly the tropics and the arctic.

Regional and local data requirements can be addressed from *in situ* measurements, sub-orbital (aircraft, drones, balloons, etc.) sensors, and targeted orbital observations. As defined herein, regional measurements focus on developing the information necessary for society to understand, manage, and predict the dynamics of the Earth system, which calls for a vigorous and comprehensive study of the terrestrial carbon cycle, terrestrial ecology, biodiversity, and land use and land cover change. Studies that focus on specific high latitude, mid-latitude, and low latitude regions are key to addressing uncertainties in global observations and models and unveiling mechanisms of regional change that are not well characterized. For example, the impact to regional biodiversity and nutrient and carbon cycling of new energy production systems must be addressed before such systems become globally important.

In the area of carbon science specifically, the top priority for regional data are more accurate, dense atmospheric carbon concentration measurements over key regions. Our current inability to quantify accurately carbon sources and sinks at regional scales (e.g. King et al., 2014; Canadell et al, 2012) is limited by (1) the lack of dense, continuous atmospheric data and (2) limits our ability to observe interactions between ecosystems and atmospheric carbon concentrations over domains where ecosystems are being influenced by climate change and human land management. Arctic ecosystems, for example, may become a significant net carbon source as a result of rapid arctic warming and mobilization of permafrost carbon pools, but current measurements may not enable accurate detection of these emissions. Globally, ecosystems are a strong net sink of atmospheric CO_2, but regional sources and sinks are poorly quantified, limiting our understanding of the processes governing these sinks. The vulnerability and resiliency of these ecosystems will ultimately determine their ability to continue to sequester carbon and mitigate climate change. Dense regional measurements are needed to observe and understand the responses of critical regional ecosystems to climate and land use change. This call for dense regional measurements in key regions is strongly echoed by other recent reports (CEOS, 2014; Moore et al, 2015)

An analysis and validation framework for carbon cycle science is needed that integrates ecosystem process models that relate surface carbon flux to meteorological data, soil state (chemistry, structure, moisture and temperature) and information on land cover composition, function and structure. As will become clear in the following sections, many of the inputs to ecosystem process models that simulate carbon fluxes are the same as those required for terrestrial ecology, land use land cover change, and biodiversity modeling. Analysis frameworks require globally consistent medium resolution observations of the land surface and 3 dimensional structure. However, models that use these data must be validated at higher resolution and these efforts are best accomplished at regional scales. Interdisciplinary work that links LULCC, terrestrial ecology, biodiversity and carbon cycle science across scales also benefits from regional observations made at high resolution, yet are comparable to observations that are made globally. Locations of rapid change, such in the vicinity of natural disasters and anthropogenic disturbance (e.g. tropical deforestation), require the rapid deployment of sub-orbital and orbital observation platforms capable of near-real time observation and analysis. New technologies for regional monitoring are particularly needed in agricultural settings where timely data on crop productivity and water and nutrient stress can be used to target application and reduce yield gaps (Lobell 2013). Such opportunities are developing rapidly due to the availability of inexpensive Unmanned Aerial Vehicles (UAVs) carrying multispectral cameras and other instrumentation. These data, when used in conjunction with calibrated data from orbital and suborbital sensors, can lead to best management practices that provide improved efficiency and production with reduced observational and modeling uncertainty.

2.0 Discipline and Measurement Group Reports

Table 1. TECLUB discipline group participants and group leads (in bold, italics).

Land Use & Land Cover Change

Andrew Elmore
Lucy Hutyra
Chris Justice
Curtis Woodcock
Geoff Henebry
Matt Hansen
Tom Loveland
Jeff Masek

Terrestrial Ecology & Biodiversity

Andy Hansen
Matthew Clark
Forrest Melton
George Hurtt
Dar Roberts
Andy Hudak
Mike Falkowski
Ralph Dubayah
Jim Irons
Dave Schimel
Scott Goetz

Carbon Cycle Science

Kenneth Davis
Colm Sweeney
Hank Margolis
Chris Williams
Randy Kawa
Ben Bond-Lamberty
Chip Miller
Mike Wulder
Lahouari Bounoua
Jim Collatz
Josh Fisher
Tomohiro Oda
Jon Randon
Forrest Hall

Measurements

Thomas Hilker
Robert Tueuhauf
Amy Neuenschwander
Bruce Cook
Nancy Glenn
Crystal Schaaf
Son Nghiem
Simon Hook

2.1 Terrestrial Ecology & Biodiversity

2.1.1 Societal Relevance

Understanding the complex, changing planet on which we live, how it supports life, and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing humanity. It is also one of the most important challenges for society as it seeks to achieve prosperity, health, and sustainability. NRC 2005.

Biodiversity is the variability among living organisms in terrestrial, freshwater, and marine environments and includes ecological, functional, taxonomic, and genetic diversity across space and time. Terrestrial ecosystems include both living organisms and their abiotic environment at local scales, and the concept of biodiversity includes variation in ecosystems at broader spatial scales of organization, such as landscapes, ecoregions and biomes. Components of biodiversity, such as species composition, abundance, and interactions, are intimately linked to ecosystem functions, such as nutrient cycling and food production (Figure 2.1).

Many ecosystem functions are important to human well-being, as they provide supporting (e.g., nutrient cycling, primary production), provisioning (e.g., food, water, fiber), regulating (e.g., climate, flood control, disease), and cultural (e.g., aesthetic, recreational) services that are essential for human well-being (Millennium Ecosystem Assessment, 2005). Humans are an integral component of ecosystems, being both dependent on ecosystem services and driving changes in biodiversity that affect ecosystem resilience, functioning and services.

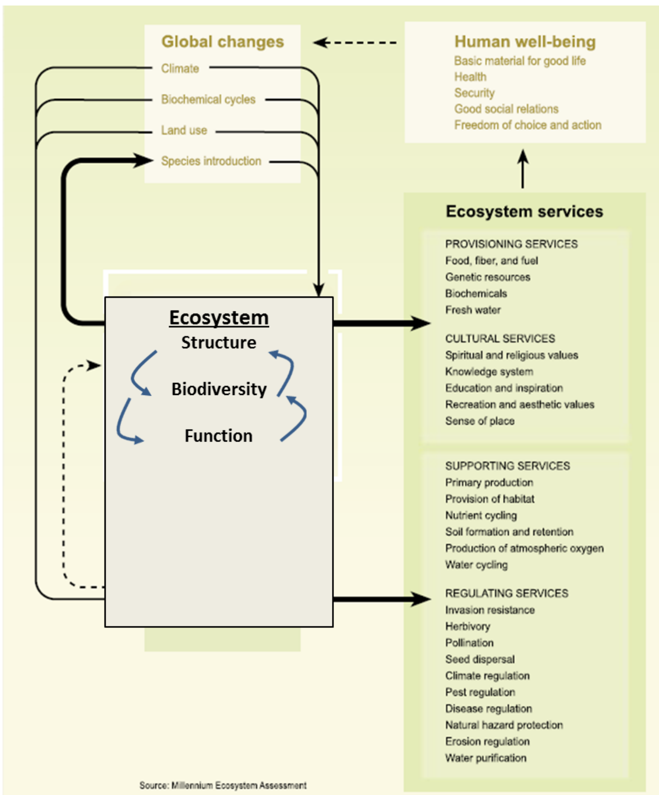


Figure 2.1 Interactions among characteristics of ecosystems, services that ecosystems provide to humans, and human well-being, all in the context of global change (Millennium Ecosystem Assessment 2005).

Humans have benefited substantially from our use of natural resources, yet our activities, particularly land use, climate change, and species introduction, are driving major losses in biodiversity and subsequent degradation and disruption of ecosystem services vital to human well-being. Consequently, there is widespread agreement among the scientific community that we need to better understand relationships between drivers of change and biodiversity, including: research to better understand interconnected ecological relationships; assessment to quantify current condition and trends; forecasting to identify possible future scenarios; and, adaptive management to learn how to sustain ecosystems and beneficial services for humans (NRC 2001, Millennium Assessment 2005, NRC 2007, Melillo et al. 2014, IPCC 2014). Direct drivers of global change (e.g., climate, land use, and invasive species) and indirect drivers (e.g., demographic shifts, economic growth) have impacts on biodiversity and ecosystems that depend on scale; therefore, we are challenged to conduct research, forecasting, and stewardship at local to global scales and through time. Approaches are thus needed that couple global trends with local factors, such as soil, topography, economic resources and culture (NRC 2007).

Space-based observations are essential for better understanding the human/ecosystem interaction in that they provide a global picture, but are spatially-resolved to provide local information. Thus, the NASA Earth Science and Applications Program has a vital role to play in the international response to global change. This section suggests the science questions, analysis frameworks, and observations by which NASA Earth Sciences and Applications can best advance understanding and stewardship of terrestrial ecosystems and biodiversity in the coming decade.

2.1.2 Science Questions

Understanding and managing feedbacks between humankind and ecosystems has been a central theme for major international and national global change programs. These programs have independently converged on an overlapping set of key questions and objectives that deal with ecosystem changes and their causes, consequences for humans, and pathways for sustainable stewardship (Millennium Assessment 2005, NRC 2007, Schimel et al. 2011, IPCC 2014, Melillo et al. 2014). Our science questions are consistent with those of previous assessments. The overarching question is:

How are ecosystems changing and what are the consequences and opportunities for sustaining the services they provide to humans?

More detailed questions include:

- *How will ecosystems change in a changing environment and are there critical thresholds that, once crossed, lead to long-term or irreversible change?*
- *How do ecosystem biodiversity, structure, and function interact to influence the provisioning of ecosystem services?*
- *What observations are required to provide early warning of abrupt ecological change?*
- *Which of the earth's ecosystems are more sensitive to global change and why?*
- *What are the consequences for human well-being of loss of ecosystem services?*
- *To what extent might reductions in ecosystem services under global change reduce human carrying capacity and what types of advances in technology would be required to offset these losses in ecosystem services?*
- *What information has the most value and utility in managing ecosystems under global change?*

If humans are both drivers of ecosystem condition and dependent on their services, then human well-being is dependent on our stewardship of ecosystems. These questions aim to understand fundamental relationships between ecosystem characteristics, ecosystem services, and consequences for humans. They also are directed towards assessing current and potential future trends in ecosystems and human well-being, and identifying thresholds under global change where ecosystem services become rapidly degraded. Knowledge of these fundamental topics lays the basis for learning how to steward ecosystems to sustain human well-being. The level of stewardship required likely depends on human population size, consumption, and technology, thus there is a need to expand the inquiry to include these factors.

These questions involve spatial and temporal scales well beyond the capacity of individual research organizations. Understanding and sustaining ecosystems and humans requires observations and analyses that span global scales over decades. But because global patterns are mediated by biophysical and human factors at finer scales, observations and analyses are also needed at local to regional scales with higher temporal frequency. The NASA Earth System Science Program is perhaps unique in its capacity to monitor the biosphere and develop data and products at global to local scales.

2.1.3 Analysis Framework

The analytical framework for characterizing, quantifying, modeling and forecasting changes in terrestrial ecology and associated biodiversity is necessarily dependent on the spatial and temporal scales of interest. We addressed both global and regional scale assessments, in the context of societal relevance (discussed above) and the identified measurement needs (summarized below) (Figure 2.2). The group agreed there is urgency in implementing various analysis frameworks because rapid changes in land use, and in climate, are impoverishing biodiversity and ecosystem function, and the services they provide to humanity (whether provisioning, regulating, supporting or cultural) (Millennium Ecosystem Assessment, 2005).

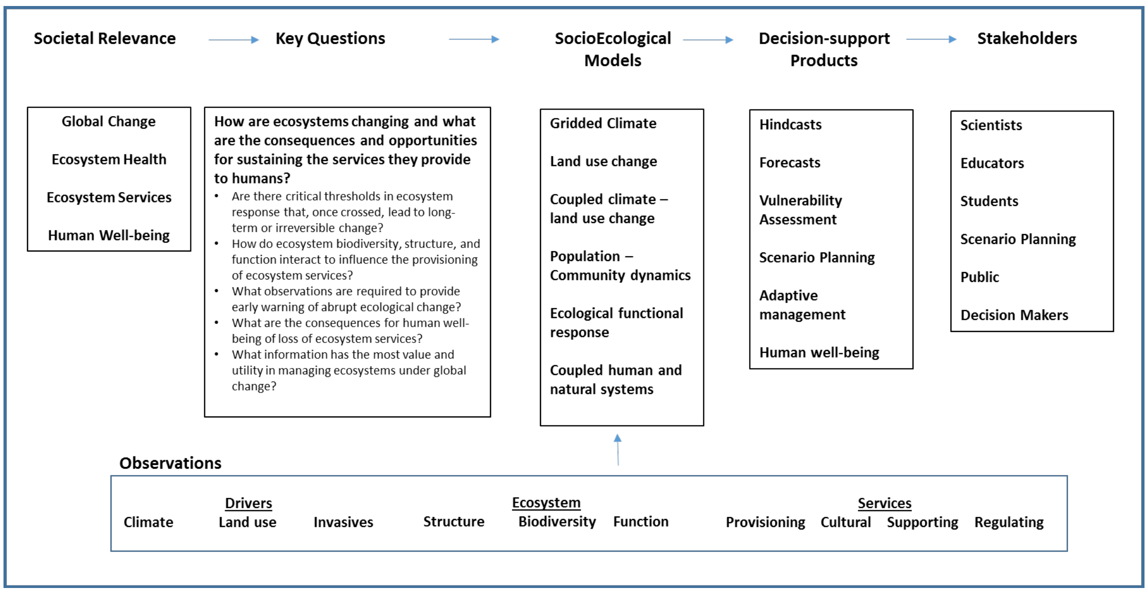


Figure 2.2 Theoretical approach for linking biodiversity and terrestrial ecology science to societal needs.

Analysis of terrestrial ecology and biodiversity requires extensive, spatially distributed observational data acquisition and analysis (Figure 2.3). Algorithms are used to extract information from observations, and models are used to derive quantitative relationships between coupled processes (like land use and climate change) that influence the patterns of ecological processes. Ecological and biogeochemical process models are also typically used to link ecosystem processes to functional attributes across scales, which requires capturing and incorporating biological mechanisms and their interactions.

2.1.4 Measurement and Data Needs

Ecological process and forecasting modeling frameworks (Figure 2.3) require substantial in situ data from distributed networks that allow one to make maximum use of spatially explicit remote sensing observations (Table 2). Those data, in turn, are critical to addressing the science questions we identified. As with the other disciplines discussed in this report, multi-source remote sensing data, and algorithms to extract information from them, are a key feature of studies characterizing and quantifying terrestrial ecology and biodiversity. But the primary interest is not in algorithm or model development, but rather the derived information applied to the science questions and their societal relevance.

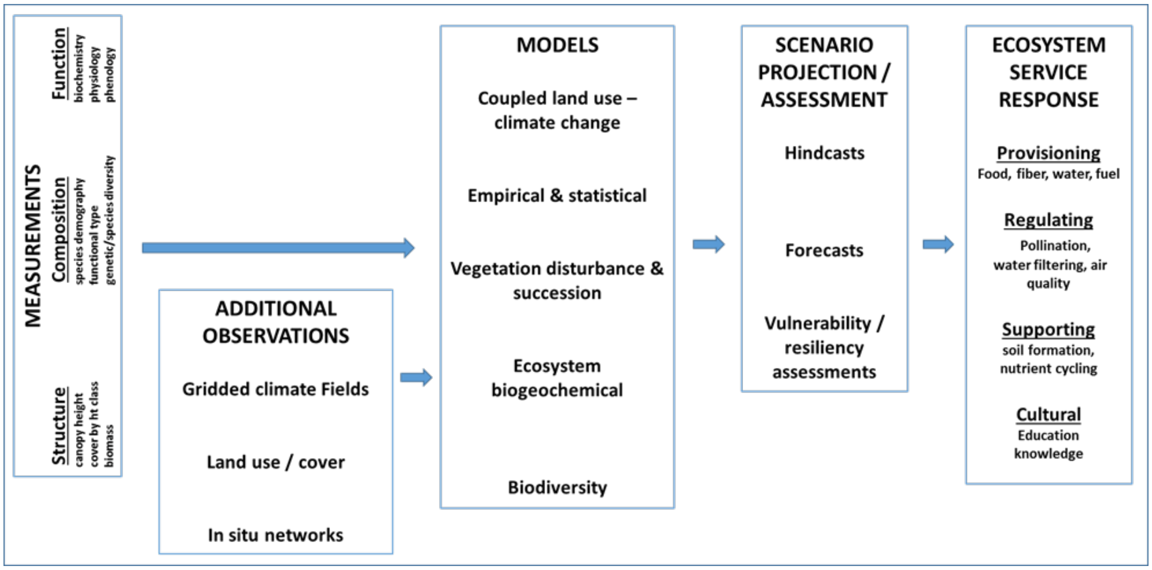


Figure 2.3. Generalized analysis framework for addressing terrestrial ecology and biodiversity science questions and measurement needs. This figure illustrates the flow of key measurement needs (top) to the overarching societal relevance (bottom). Models and observational data are used in a coordinated way to address the primary science questions.

At global scales, *continuity in moderate spatial resolution (~30m) remote sensing observations* would best provide the essential information for extending existing measurement records and their application to terrestrial ecology and biodiversity assessments, monitoring and forecasting. At the same time, *additional finer-scale (few meter) information is needed regionally*, in a sampling mode, to link in situ measurements to the moderate resolution imaging sensors used to map biophysical properties across both regions and the globe. Moreover, *3D vertical structure information* is needed to provide unique information on habitat heterogeneity that cannot be captured in typical optical imaging sensor data sets, and to inform and improve what structure information can be derived from imaging radar. These higher resolution and vertical structure data are particularly essential for characterizing biologically diverse areas that are especially vulnerable to rapid change, as is occurring across the Tropics from pulse disturbances like deforestation and other rapid forms of land conversion, and press disturbances like climate change.

2.1.4.1 Ecosystem Structure

Structure, function, and composition are intimately interconnected ecosystem properties. Ecosystem structure could be defined as the 3-dimensional organization of biophysical objects in the scene from a remote sensing standpoint, making structure the ecosystem property most amenable to remote characterization, at least at a single point in time. Such "snapshot" characterizations are used to infer fundamental ecosystem structure attributes like vegetation cover, height, biomass, leaf area index (LAI), etc. Remote sensing synoptically captures or samples these structure variables at spatial frequencies sufficient to capture spatial patterns, thus providing a means to upscale functional processes to the ecosystem level.

Active sensors provide a third dimension that makes remote characterizations of ecosystem structure all the more accurate and powerful. Lidar data in particular provide exceptionally dense characterizations of 3D canopy structure that open a plethora of possibilities to scientists and managers, compared to passive optical sensors that lose sensitivity in high biomass vegetation. Knowing just canopy height alone, as measured (not predicted) from lidar, greatly reduces the uncertainty associated with estimates of biomass, volume, and other vegetation structure attributes. Additional structural information is contained in the distributional shape of the canopy height profile used to summarize the distribution of lidar returns, and 3D approaches add yet another level of aggregated information, yet we are still only beginning to mine the tremendous information content within lidar point clouds.

Lidar can provide accurate estimates of structure variables like LAI profiles (for ecophysiological models) and canopy bulk density (for fire behavior models) that are critically important as physical model drivers yet exceedingly difficult to measure by other means, either remotely or on the ground. We anticipate that information in the point cloud will be used to model transfer of heat or gas exchange within the canopy, or elucidate the habitat preferences of specific birds or other species of concern.
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.

2.1.4.2 Ecosystem Composition

Ecosystem composition includes demographic (mortality, growth, dispersion), functional (species/area multiplied by function, Plant Functional Type (PFT)) and taxonomic (genetic composition, species presence/abundance) elements. Demographic components imply time series, either tracking seasonal, annual, interannual or multi-year changes in live canopies and forest regrowth. Fundamental data needs include at least annual sampling to capture ephemeral events such as forest degradation and preferably seasonal observations to capture the timing of disturbance events or fine scale disturbance. Broad-band sensors, such as the Enhanced Landsat Thematic Mapper are sufficient and can capture events even at sub-pixel scales, but functional diversity (e.g. plant species or PFTs mapped using remote sensing) has primarily required spectroscopy (Schimel et al. 2015).

There are direct linkages between leaf-level plant chemistry, canopy structure and spectral diversity (Asner et al., 2014). These linkages have enabled researchers to map plant species using imaging spectrometry in Mediterranean, temperate, savanna and tropical ecosystems. Seasonal spectroscopy has been shown to improve species discrimination, requiring at least one observation per season. Specific, minimum wavelength requirements have not been assessed, but comparison between spectroscopic and broad band sensors has shown higher accuracies using imaging spectrometry (Clark et al., 2005), a need for sampling within all broad spectral regions (visible, near-infrared and short-wave infrared), and greatest species-discrimination in the SWIR (Feret and Asner, 2014). Spatial resolution requirements are ecosystem dependent with highest accuracies achieved at object scales in tropical ecosystems (i.e. crowns; Clark et al. 2005), but coarser resolutions sufficient in lower diversity temperate systems with larger patch sizes (e.g. 40 m in mixed conifer, broadleaf forests Schaaf et al. 2011).

Taxonomic diversity has been evaluated through either a combination of fine temporal sampling to capture phenologically expressed diversity measures or using spectral vegetation indices and imaging spectrometry. Phenologically derived measures require seasonal data (at least three samples in a year) with spatial resolution requirements depending upon patch size. Spectroscopic measures require at least one observation per year, particularly in seasonally deciduous regions, but may not necessarily require fine spatial resolutions.

2.1.4.2 Ecosystem Function

Ecosystem function can be broadly defined according to categories of plant, canopy, and ecosystem-level attributes that characterize and track ecosystem response to climate and other human induced impacts. Functional attributes, listed in Table 2, provide detailed information that can be leveraged to improve ecosystem management in light of existing and future threats. In the short term, climate change and other human activities impact ecosystems primarily by altering energy and matter fluxes, which ultimately have long-term impacts on ecosystem function. For example, drought causes near-term changes in plant water content, which in the longer term alters plant water content and ultimately increases an ecosystem’s vulnerability to disturbances such as wildfire. Severe wildfires can cause irreversible ecosystem change by altering species composition and vegetation structure. Detecting early signs of ecosystem change through remote sensing of functional variables related to biochemical, physiological, and ecosystem processes is critical for improved management of changing ecosystems under increasing threats.

The spatial and temporal resolutions required for measuring functional attributes is largely driven by the compositional, structural, and functional heterogeneity of ecosystems as well as temporal dynamics of critical ecosystem processes. Ecosystem composition, structure, and function vary across multiple spatial and temporal scales. Studies of regional and global biogeochemistry or phenology have leveraged MODIS data at 250-, 500-, and 1km spatial resolutions, while studies exploring ecosystem community change, habitat heterogeneity, and biodiversity indicate a requirement for higher spatial resolutions (e.g., 30-150 m). Spatial resolution requirements for assessing functional attributes must also balance temporal resolution and global coverage requirements for critical functional attributes. For example, ecosystem function such as productivity are associated with changes in the timing and duration of the growing season and thus characterizing interactions between climate and ecosystems requires precise detection of the start and end of the growing season and phenophases. The uncertainty in phenophase estimates increases with decreases in both spatial resolution (Hufkens et al., 2012). The longest revisit time acceptable is less than bi-monthly, but is also dependent on cloud cover and other interferences thus may not always be achieved. Sensor pointability or constellations would enhance remote sensing based assessments of ecosystem function by offering the opportunity to increase temporal resolution, while maintaining spatial resolution, in areas with persistent clouds (e.g., the tropics) or other critical areas and during key times or events (e.g., vegetation green up or onset of senescence). More specifics on measurements for terrestrial ecosystem structure, composition and function are found in section 3.

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2.2 Land Use and Land Cover Change

2.2.1 Societal Relevance

The Earth's surface is rapidly changing through human use of land, which impacts the sustainable provision of food, water, energy, clean air, biodiversity, and human livelihoods. The extent to which these ecosystem services are impacted by human land use is influenced by the effectiveness of land management, which can be improved through policy changes that incorporate careful analysis of recent relationships between policy, human livelihoods, and land use and land cover change (Lambin and Meyfroidt, 2011). For example, agricultural intensification and expansion (Tilman et al., 2011, Foley et al., 2011) influence most aspects of the earth system, including trade-offs and interactions between carbon sequestration (Burney et al., 2010), water use (Jackson et al., 2005), and biodiversity(Kleijn et al., 2006). These complex interactions can only be evaluated through the study of multitemporal observations of land use, land cover, and land condition change and analyzed within the context of human drivers and outcomes.

2.2.2 Science Questions

Where, how, and why is land use changing around the world and what are the consequences?

This core science question motivates additional, more specific questions in the area of LULCC, including:

1. *How do rapid land use and land cover changes influence regional to global weather and climate, possibly threatening agricultural systems?*
2. *How vulnerable or resilient are different land use systems to natural hazards?*
3. *How will land use policy aimed at adapting to and mitigating the effects of climate change affect food and water security?*
4. *How are competing demands for land to produce fossil fuels, bioenergy, food, feed, fiber, water, and biodiversity conservation affecting land use change processes?*
5. *Where are incentives for carbon sequestration and carbon trading influencing land use change processes?*

2.2.3 Analysis Framework

The overall analysis framework (Figure 2.4) for studying land use requires (i) observations of recent land cover and land use trends across the globe; (ii) information on social, economic, and environmental drivers responsible for those trends; (iii) observations and information on the human outcomes derived from land use and land cover change; and (iv) models capable of integrating both human and environmental drivers and impacts into projections of future trends in land use. Nearly a quarter of Earth's terrestrial surface has been cultivated, and the majority of lands unsuitable for cultivation are also under continual management (Foley et al., 2005). Thus, the study of land dominated by humans, requires spatially extensive data acquisition and analysis. The spatial and temporal scales of observation and analyses must be fine enough to detect and

characterize landscape variability and change created by land use with sufficient frequency to connect changes with events and drivers (i.e., scales relevant to land management: 15-30m and 3-4 days), motivating the use of high-quality 30-m spatial resolution data at global extents with a subweekly return interval.
Synergistic use of multi-source data will continue to be a key feature of studies characterizing and quantifying land use and land cover change. Advances in the number and type of sensors acquiring LULCC-relevant data leads to the need for further investment in algorithms for effectively integrating multi-source data. For example, recent advancements in the fusion of airborne LiDAR surveys with high-resolution optical satellite data have lead to new insights into vegetation structure within urban settlements (Raciti et al., 2014). Similarly, reducing uncertainty in models and predictions of land use change processes requires a stream of high-quality high-resolution data sampled at sufficient intervals to validate and refine model predictions and improve model performance (e.g., Schroeder et al., 2008, Wulder et al., 2010). Provision of calibrated, orthorectified, integrated products from multiple sensors and made available at management-relevant spatial and temporal scales advances the science of LULCC by enabling collaboration between social, biological and physical scientists in these areas, thus ensuring the continued advancement of LULCC interdisciplinary science.

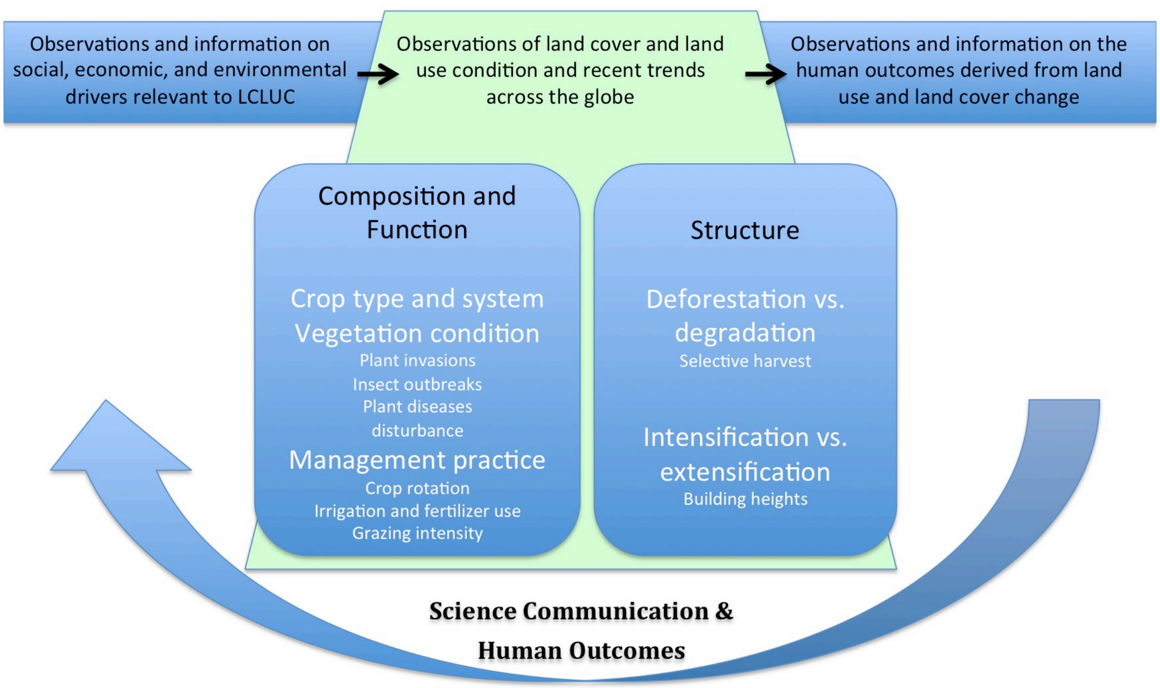

Figure 2.4: Analysis frameworks for the study of land use and land cover change integrate drivers and impacts of change through the analysis of multi-spatiotemporal observations of land cover. Improvements in the measurement of land cover composition, function, and structure all lead to understanding of how policy can improve sustainability and human outcomes.

2.2.4 Measurement and Data Needs

First LULCC Priority

A 3 day revisit frequency of 30m optical data (Vis to SWIR, and thermal) would lead to cloud-free observations at ~weekly intervals, enabling detection, quantification and characterization of rapidly changing land surfaces.

Food, water, and energy security, human health, and the protection of natural systems are among the most pressing problems facing humanity. We are limited in our ability to address these problems due to a lack of temporally rich data at scales relevant to land management, constraining our capacity to characterize and quantify land use and land cover changes. This is particularly true for efforts to characterize rapid and short-term changes and dynamics, necessary to understand ecosystem functioning at global scales. The limitations in the current moderate-resolution observation record is particularly acute in high latitudes and the humid tropics.

By building from the long time series currently available but increasing the temporal frequency, we seek to enable near real time analysis, develop early warning systems, improve projections of future land use and land cover, and provide better decision support at human scales. The key measurement requirement for characterizing land use is *seasonal phenology at the scale of land management.* Retrieving the phenology of individual land parcels allows identification of vegetation type, condition, and management practice, including crop type and cropping system (e.g., Wardlow et al., 2007). Aspects of vegetation condition that could be assessed with such data include plant invasions (Wilfong et al., 2009), insect outbreaks (Foster et al., 2013), plant disease, plant stresses, and short-term disturbances such as fire and drought (Kennedy et al., 2010, Powell et al., 2010, Hansen et al., 2010). Cropping system characteristics such as planting and harvest dates, irrigation amount and frequency, tillage practices, and fertilization intensity would all be enhanced by medium-resolution, high-temporal frequency optical data. Land cover classification for Arctic and sub-Arctic ecosystems are highly variable, particularly in Eurasia. This presents a challenge when trying to understand the relative importance of different ecosystem/plant functional types in the context of climate change In general, there is an element of timing to many measurements relevant to LULCC science that has not been well represented due the lack of data at appropriate spatial and temporal scales. Harnessing this temporal domain for characterizing land vegetation has been a primary strategy since the beginning of remote sensing (Badhwar, 1984) and has become foundational to application of the AVHRR and MODIS data records (DeFries et al., 1995, Hansen et al., 2002, Lunetta et al., 2006). Recently, time series analysis approaches and computing advances have opened opportunities for global phenology retrievals at 30m resolution (Yan and Roy, 2014, Elmore et al., 2012, Roy et al., 2010). However, full potential will not be realized until the temporal density of moderate-resolution imagery is improved. Free and open access to analysis ready image products has, since 2008, provided an insight into the potential available when combining both spatial and temporal domains over large areas (Wulder and Coops, 2014). Only recently have the benefits of this capacity been illustrated (e.g., Hansen and Loveland, 2012, Hansen et al., 2013) resulting in an expansion of aspirations regarding information needs and science questions to be addressed.

The key satellite observational requirements supporting this measurement are:

1. *Passive optical multi- or hyper-spectral data.* The current Landsat, SPOT, and ASTER archives provide 42 years of observations at <60m resolution (30 years at 30m resolution), and have provided the foundation for understanding the characteristics of natural and managed ecosystems globally. While radar data can effectively supplement passive optical observations, the land use community continues to rely on the long-term observations through the visible and infrared to monitor land condition.
2. *Data resolution of 30m or finer* is required to identify individual units of land management (farms, forest concessions, ranches, etc). While observations at 300-1000m resolution have proven invaluable for understanding regional linkages between climate and vegetation, the local impacts of land management are cryptic at this coarse resolution (Wulder et al., 2008). The finer scale is also important for separating human-induced versus natural land changes.
3. *Temporal resolution of ~3 days*. Separating vegetation types (particularly crop type) is best accomplished using spectral phenology curves with ~weekly time step. The GEO-GLAM (GEO Global Agricultural Monitoring) framework, for example, requires cloud-free observations every 8-days, and USDA National Agricultural Statistics Service (NASS) strives for a similar temporal density. Studies have demonstrated that 8-day coverage requires satellite observation frequencies of ~2-3 days in the face of cloud cover, particularly during the "spring" green-up period (Whitcraft et al., 2015, Ju and Roy, 2008).

Dynamic changes in land cover as it responds to changes in land use and external forces such as climate change reveal the functioning of land, and thus have a strong control on productivity and the provision of food, water and energy. Yet due to our historical treatment of land use and land cover as a more-or-less static, thematic map at 30-m resolution, we know little about the temporal frequency of change. This knowledge gap stems from the lack of quality observations to characterize land use dynamics at the space and time scales at which they occur. *Increasing the temporal frequency of global 30-m observations is a direct and effective way of enhancing LULCC science in all of the sub-areas listed above.*

Second LULCC Priority

Seasonal, long-term, global, high (1 - 10m) spatial resolution 3D observations of the Earth's surface capturing vertical structure to enable enhanced characterization and quantification of land cover and land use change.

Spaceborne LiDAR offers synoptic, systematic, and repeatable measures of both ground and above ground elements, including habitat, biodiversity, and carbon sources and sinks (Hall et al., 2011). Sustainable management of land resources requires detailed information on vegetation types (e.g., grass, shrub, tree) and structural differences within vegetation types. Current capabilities for characterizing land cover globally lack the third dimension (vegetation height and structure), introducing uncertainties in land cover characterization. High spatial resolution measurements are required to capture the local variation present in bare ground and above-ground features, such as vegetation canopies and the built environment. A primary example is forest three-dimensional structure, which is related to habitat quality (Goetz et al., 2010), disturbance dynamics, and tree mortality (Clark et al., 2004). The differentiation between deforestation, degradation, and selective harvesting in particular has long been a challenging forest attribute to map (Nepstad et al., 1999), yet is widely recognized as key to the successful implementation of REDD+ protocols. Similarly, changes in the three-dimensional structure of vegetation associated with the migration of shrub-grassland and forest-alpine boundaries is not ideally studied with optical data, yet these changes are already occurring (Pearson et al., 2013) with important implications for adaptation and mitigation of climate change (Myers-Smith et al., 2011).

The impacts on LULCC science of three-dimensional observations of the earth's surface extend far beyond forest structure. The expansion of urban settlements has fundamentally altered the earth surface, regional climate, biodiversity, and the exchange of carbon and nitrogen with the atmosphere (Grimm et al., 2008). Settlements are three-dimensional structures, yet most research to date has treated them as simple changes to land cover, therefore ignoring important attributes such as building height, which is an important indicator of urban intensification and regulator of earth system processes in urban environments (Grimmond and Oke, 1999). Vegetation biomass, height, and spatial distribution also relate strongly to urban processes and the success of management practices, and would be best-studied using data that includes information in the third-dimension (Raciti et al., 2014). Finally, most models that predict the expansion of settlements use topography as a highly significant state variable, and would be improved through the acquisition of more accurate, globally consistent data.

The success of these proposed measurements depends strongly on the specific measurement characteristics. The key satellite observational requirements supporting this measurement include:

1. *3D observations of the Earth's surface*: Satellite and airborne measures with laser instruments have provided unique insights into biome-wide forest structure and function (Neigh et al., 2013), while also providing otherwise unavailable information on urban systems (Yan et al., 2015). As direct measures of the ground and above ground elements, LiDAR uniquely provides information on the intensity of land use and related change over time.
2. *Seasonal, long-term, global, high (1 - 10m) spatial resolution*: Multiple measurements per year are critical to support international treaties and related compliance. Given asymptotic relationships between vegetation complexity and optical spectral measurements, LiDAR offers independent insights on both growth and depletions in vegetated ecosystems. 1 to 10 m spatial resolution is required to capture the variance present in natural environments (Wulder et al., 2013). More coarse spatial resolution results in an averaging of the vertical conditions present

limiting the measurement power (with measurement outcomes analogous in quality to those based upon modeling supported by optical data).

3. *Sub-meter vertical structure to enable enhanced characterization and quantification of land cover and land use change*: to capture growth and change over time, sub-meter precision in measurement is required. The vertical sampling density will essentially indicate the types of changes that can be captured and how long an interval must pass before a change can be confidently identified.

Third LULCC Priority

Sample high-resolution (sub-meter) optical data globally for scientific calibration and validation collected "simultaneously" with 30-m data

The effective management of land for the provision of food, water and energy requires data and analysis frameworks to characterize, quantify, and predict land use and land cover change. These pursuits are best served when observations are properly calibrated and validated against high quality, higher-resolution reference data. Over the last decade this was clearly demonstrated, albeit at lower resolution, by the use of ASTER data to validate MODIS observations (e.g., Morisette et al., 2005). High-resolution (sub-meter) optical data collected sufficiently contemporaneously with 30-m data to permit the calibration of moderate resolution land cover and land use change algorithms and models. This would be particularly useful in areas exhibiting high spatial heterogeneity in land cover quantities, or across rapid land cover gradients. The characterization of how spatial patterns apparent in 30-m data arise from features observable at finer resolution is possible in only limited areas, yet has the potential to improve the validation of regional and global products, increasing the confidence and use of regional to global estimates of land use and land cover change.

High resolution (sub-meter) data obtained simultaneously with moderate resolution data are currently unavailable or sparsely available for much of the world, slowing the pace of algorithm development and weakening our confidence in conclusions derived from medium resolution data. The need for simultaneous data for validation is due to the rapid land surface changes and the atmosphere. High-resolution optical data are not required to be wall-to-wall but would be collected on a systematic sample basis. The availability of such data would enable multi-scale sampling strategies to be developed and applied for data acquisition by region, time and application. It would also be advantageous to use such observations in near real-time, targeting the collection of regions of Earth experiencing rapid change (e.g., wildfires, extreme events and disasters). Although it wouldn't reliably meet the need for contemporaneous imagery, high resolution imagery for LULCC applications could include "small sat" constellations that are being implemented by private sector organizations like Planet Labs and GeoEye, to the extent those data are available at low or no cost to the non-profit science community. Additional high resolution imagery could be contributed by aircraft campaigns, including UAVs, which would be particularly useful in areas experiencing rapid change.

The success of these proposed measurements depends on their compatibility with simultaneously collected medium-resolution data. The key satellite observational requirements supporting this measurement include:

1. Simultaneously collected observations acquired by a high-resolution sensor bore-sighted with a medium resolutions sensor, as was done with ASTER and MODIS. Although land use changes occurring over periods of less than 24-hrs are comparatively rare, dynamic atmospheric conditions and sun and sensor angle considerations suggest that true calibration and validation of new LULCC algorithms requires consistent sensor geometry and simultaneous data acquisition.
2. Spectral characteristics of the required high-resolution sensor should be closely comparable with the medium resolution data collected simultaneously. This suggests a minimum requirement would be two visible bands, a near infrared band, and a short wave infrared band.
3. Likewise, spatial characteristics should consider the spatial resolution of the moderate resolution sensor and use a resolution that is an appropriate factor of the larger pixel sizes. Ideally, 3m resolution data would be used resulting in a factor of 10 higher resolution (3x3m vs. 30x30m pixels), or 100 high-resolution pixels for each medium resolution pixel.

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2.3 Carbon Cycle Science

Anthropogenic climate change is being driven primarily by human-induced increases in the atmospheric burden of carbon dioxide (CO_2) and methane (CH_4) (Stocker et al, 2013; Montzka *et al.*, 2011; Dlugokencky *et al.*, 2011). Terrestrial ecosystems play a major role in the atmospheric carbon cycle (LeQuere et al, 2009). Globally, photosynthesis and respiration from terrestrial ecosystems account for annual fluxes of CO_2 to and from the atmosphere that are nearly ten times the magnitude of anthropogenic emissions. Ecosystem sources and sinks, however, have remained nearly in balance over recent decades; the net flux is a sink of about ¼ of anthropogenic emissions (Stocker et al, 2013). Nonetheless, ecosystems are currently causing a net removal of CO_2 from the atmosphere by an unclear combination of factors such as fertilization by elevated CO_2 or N-deposition, or trends in light, temperature, or moisture (Stocker et al, 2013; Friedlingstein et al., 2014; Arora et al., 2013). This acts to slow climate-change effects. In terms of CH_4, terrestrial ecosystems, including agriculture, include more than 50% of all sources to the atmosphere. While the global balance of terrestrial carbon fluxes is well known, biome-level fluxes are poorly constrained (Peylin et al., 2013; King et al., 2014), and the response of the terrestrial carbon cycle to changing climate and land use is a primary source of uncertainty in climate projections for the coming decades to centuries (Friedlingstein et al., 2014; Jones et al., 2013).

Ecosystem-climate interactions are not limited to the carbon cycle. Ecosystem carbon and water cycles are closely coupled, and strongly influence the earth's surface energy balance (Campbell and Norman, 1998). Eco-hydrological processes have broad impacts on weather, climate and water resources. The increase in atmospheric CO_2 is also leading to increasing acidification of the earth's oceans (Orr et al., 2005). Increased understanding of the terrestrial carbon cycle is thus complementary to a deeper understanding of the earth's energy and hydrologic systems.

Anthropogenic emissions of CO_2 and CH_4 are intermingled in the atmosphere with terrestrial ecosystem GHG fluxes (Pacala et al., 2010; Andres et al., 2012). Economic data regarding fossil fuel consumption serves to constrain CO_2 emissions at a global scale, but regional emissions are less certain (Marland et al, 2009; Guan et all, 2012). Emissions of CO_2 caused by land use change and anthropogenic CH_4 emissions are also not well quantified (Houghton et al., 2012; Brandt et al, 2014). Future anthropogenic emissions of CO_2 and CH_4 are highly uncertain; they represent a large source of uncertainty in future climate projections (Stocker et al., 2013).

2.3.1 Societal Relevance

Humanity must understand, predict, and manage the dynamics of the earth's climate system, necessitating vigorous and comprehensive study of the terrestrial carbon cycle, including its ecosystem and anthropogenic components (Michalak et al., 2011).

Understanding: The scientific community must provide timely understanding of the magnitude and causes of current changes in atmospheric CO_2 and CH4. This fundamental understanding underlies our ability to predict and manage future climate change.

Prediction: The scientific community must provide the best possible understanding of future carbon sources and sinks to enable society to make informed and effective choices regarding managing and adapting to future climate change and impacts of the carbon cycle on ecosystems.

Management: The scientific community must develop transparent and effective methods that allow us to evaluate the efficacy of measures taken to manage CO_2 and CH_4 sources and sinks. This requires methods that can quantify and monitor carbon sources, sinks and stocks with the accuracy and precision necessary to enable policy implementation and provide guidance for management decisions. Policy and management often occur at local to regional scales so evaluating sources and sinks at these scales is critical. However, the links between regional GHG fluxes and global climate are complex (see §2.3.3.3 below) and understanding these linkages is also a major priority. Therefore, regional scale studies become a focal point for linking management activities to global climate.

2.3.2 Science Questions

Addressing these societal needs calls for answers to the following scientific questions:

Understanding: Which of the earth's terrestrial ecosystems are slowing climate change by absorbing carbon from the atmosphere? Are any terrestrial, aquatic or coastal zone ecosystems destabilizing and releasing carbon to the atmosphere? If so, where is this happening and at what rate? What are the mechanisms driving the imbalances in ecosystem fluxes? What are current anthropogenic emissions of CO_2 and CH_4?

Management: What are the impacts of human choices on the carbon cycle, e.g., land management, economic incentives, dietary choices, policy choices? What adaptation strategies might be effective in providing increased resilience of ecosystem goods and services and what are the consequences for the terrestrial carbon cycle?

Prediction: How are terrestrial and anthropogenic carbon fluxes going to change in the coming decades to century?

These questions are generalizations of a number of pressing research questions focused on particular biomes or anthropogenic processes.

<u>2.3.2.1 High latitude ecosystems:</u> Will the warming climate thaw frozen soils or increase wildfire extent and intensity, releasing large amounts of currently sequestered carbon into the atmosphere, accelerating climate change? What are the relationships among hydrology, topography, fire, permafrost thaw, and ecosystem carbon dynamics under a changing climate? How important is increased shrub growth to the northern carbon budget?

<u>2.3.2.2 Mid-latitude ecosystems:</u> What are the processes causing the current sink of carbon in mid-latitude ecosystems? Can these processes be managed to enhance the carbon sequestration of these ecosystems? How vulnerable are carbon stocks to release from mid-latitude drought episodes and associated ecosystem stresses and disturbances?

<u>2.3.2.3 Tropical ecosystems:</u> Are undisturbed tropical ecosystems currently a source or a sink of carbon to the atmosphere? How are these highly productive ecosystems responding to climate change and increasing atmospheric CO_2? How are changes in land use and resource management associated with the rapidly developing economies in the

tropics altering the carbon balance of these ecosystems? Can we develop robust monitoring and verification systems that will allow us to determine to what extent policy initiatives such as REDD and REDD+ are effective in reducing atmospheric GHGs?

2.3.2.4 Coastal and terrestrial aquatic ecosystems: How are rising sea levels, ocean acidification and human development altering carbon- and species-rich coastal ecosystems? Can these systems be managed both to preserve biodiversity and enhance carbon sequestration? Can we close continental carbon budget by better documenting coastal carbon dynamics?

2.3.2.5 Cities: What attempts can be made to avoid and mitigate greenhouse gas emissions in cities? How effective are the attempts currently underway? Can we develop transparent and verifiable measurements of carbon emissions from urban environments? Can we better constrain fossil fuel emissions, both spatially and temporally, so allow better comparisons with models and flux measurements?

2.3.2.6 Energy production systems: How will the carbon balance be altered by changing energy and transportation systems? What are the lifecycle carbon budgets of new natural gas production technologies, biomass/bioenergy crops, and coal with carbon capture and storage? What is their impact on atmospheric GHG concentrations?

The answers to these questions will enable decision makers to understand, predict and manage the contribution of the carbon cycle to the earth's climate system.

2.3.3 Analysis Framework

As noted in section 1.5.4, an analysis and validation framework is needed that integrates ecosystem process models that relate surface carbon flux to meteorological data, soil state (chemistry, structure, moisture and temperature) and information on land cover composition, function and structure. Figure 2.5 outlines a framework in which validation of these models is accomplished by a network of tower and chamber measurements of fluxes (e.g. AmeriFlux) and *in situ* and remote sensing observations of the temporal and spatial variation in atmospheric carbon concentrations subsequent to the atmospheric transport of the surface fluxes using models. The carbon analysis and validation framework then imposes additional requirements for the atmospheric concentration data as well as needed improvements in the models. Many of the inputs to the models are the same as those required for biodiversity/terrestrial ecology and land use land cover change, as detailed earlier and summarized in Table 2.

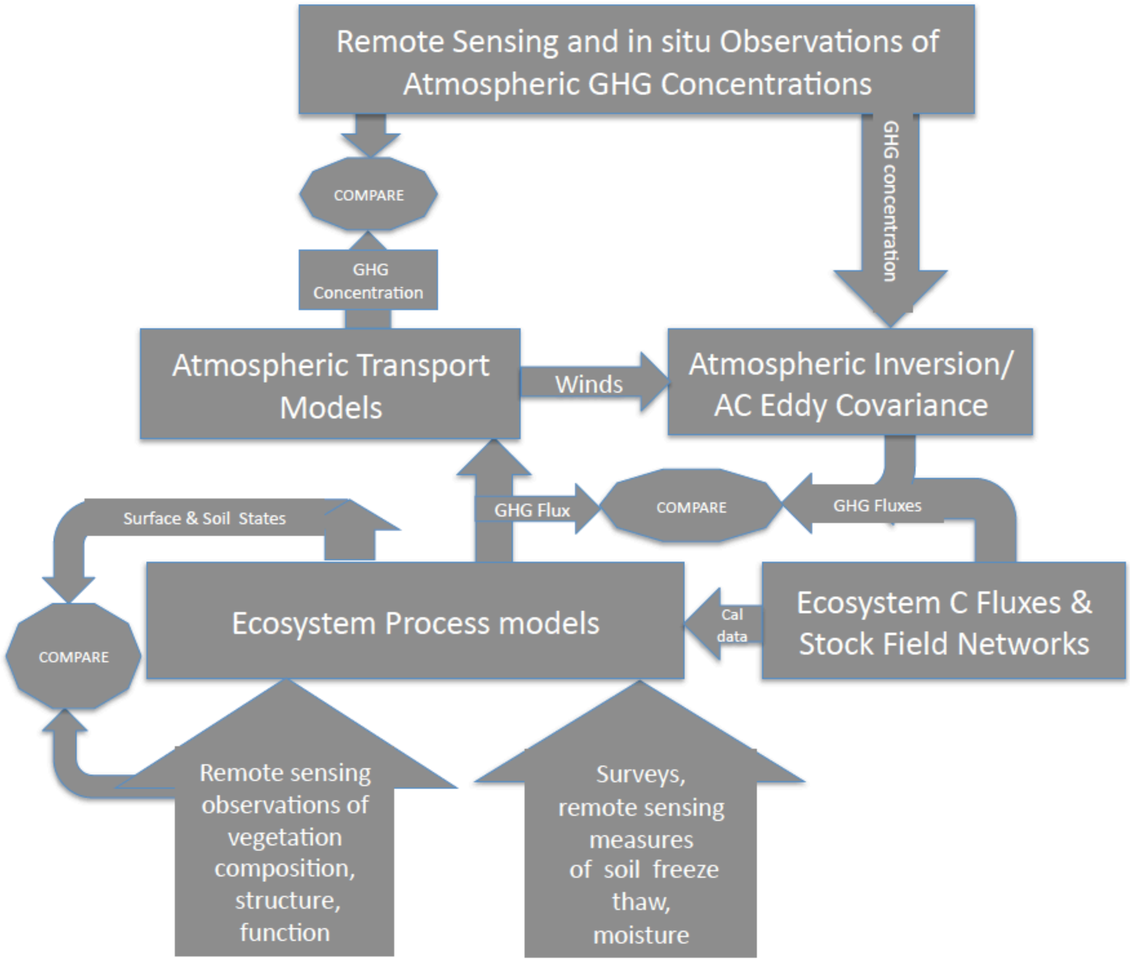

Figure 2.5: Carbon analysis and validation framework.

Carbon cycle science can be addressed, broadly speaking, at three different spatial domains: *global, regional, and local.*

2.3.3.1 Global analyses are essential to understand the aggregate impact of all processes on the global atmospheric greenhouse gas budget. We know from global analyses, for example, that atmospheric CO_2 has been increasing over the last decade at a rate of approximately 2 ppm per year but with large interannual variability that is not well-understood (LeQuere et al., 2009). This global understanding, based-primarily on atmospheric measurements, is often described as a "top-down" method. Additional tracers such as O_2 and carbon isotopes enable some disaggregation of the mechanisms of sources and sinks (e.g. oceanic vs. terrestrial fluxes, Battle et al., 2000).

2.3.3.2 Local analyses are critical to understanding the processes that govern the carbon cycle. For example, laboratory- or field-based manipulative experiments can be used to determine how ecosystem respiration and photosynthesis respond to elevated atmospheric CO_2 or changing climate (Walker et al., 2014). The response of ecosystem carbon and water fluxes to climate variability can be monitored for years using eddy covariance measurements. Ecosystem carbon stocks can be monitored with in situ biomass measurements. These local, or plot-level studies are the foundation of our process-level understanding of the carbon cycle. Extrapolating these to larger spatial domains is often described as a "bottom-up" approach to quantifying ecosystem carbon fluxes and stocks (Pan et al., 2011).

2.3.3.3 Regional analyses offer a key method for connecting process understanding and global trends (CEOS, 2014). It is the domain where so-called "top-down" and "bottom-up" methods can be brought together (Figure 2.6, Ogle et al., 2015) translating the process-level knowledge gained at local scales toward a quantitative understanding at larger scales. Regional scale analyses are also important because they operate at the scale of decision-making as well as at key scales at which climate change and human management impact the carbon cycle regionally. Accurate and precise regional analysis frameworks (Schuh et al., 2013) are an integral part of the portfolio of approaches needed to answer the key science questions in terrestrial carbon cycle science. Merged top-down and bottom-up methods (Figure 2.6) are required for effective regional analysis.

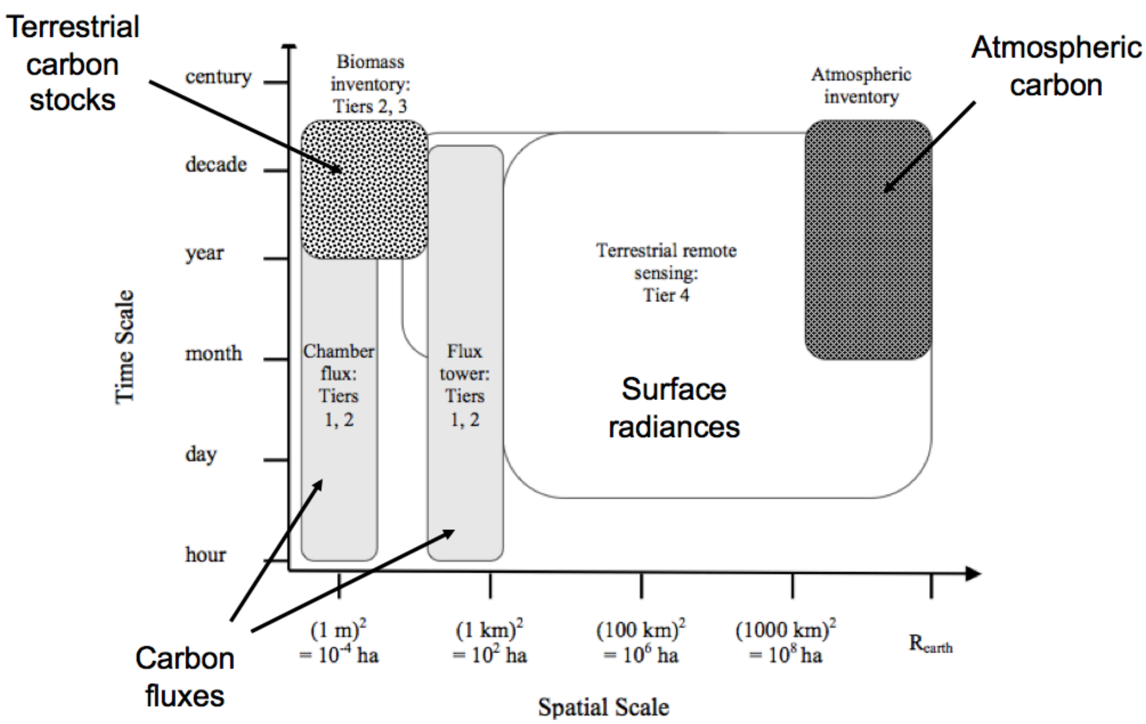

Figure 2.6 Spatial and temporal scales of data (Davis, 2008) for analysis and validation of the carbon cycle analysis framework (Figure 2.5).

2.3.3.4 Analysis framework needs:

Figure 2.6 illustrates the native spatial domains of current terrestrial carbon cycle analysis systems. Remote measurements of atmospheric gases provide strong constraints on the globally integrated terrestrial carbon cycle. A variety of methods (manipulative experiments, biomass and flux observations) enable local-scale process understanding to be obtained. Both these global and local data can be extended over long time periods, and merged in an integrative analysis framework (Figure 2.5). Continued development of global and local understanding, including advanced understanding of processes such as ecosystem disturbance and below-ground terrestrial carbon cycling, are essential to advancing our understanding of the terrestrial carbon cycle. Bridging the gap in the spatial domains of these methods, however, is essential.

The analysis frameworks required to bridge this gap include:

i) regional atmospheric budgets and inversions;

ii) upscaling of process-based, local-scale understanding of the terrestrial carbon cycle to regional domains;

iii) cross-validation efforts, both within and across methods, to evaluate the rigor of our predictive understanding of the terrestrial carbon cycle.

Questions concerning prediction or projection of the future carbon cycle require additional analysis frameworks, most notably high-fidelity, process-based, regional- to global-scale carbon cycle models. Existing ecosystem carbon cycle models show tremendous variability when used to project future fluxes (e.g. Friedlingstein et al., 2014). Continued development, testing and validation of these models with observations and experiments are necessary. In addition to accurate regional-scale diagnoses of contemporary carbon stocks and fluxes these analyses will require:

iv) local and regional scale carbon cycle observations extended over years to decades, creating a direct observational record of the responses of ecosystems and human systems to climate and atmospheric composition change, and human management choices.

v) observations across climate and management gradients that can be used to exchange space for time, thus to examine how climate change and management are likely to alter the future terrestrial carbon cycle.

vi) manipulative experiments for quantification of the sensitivity of fluxes to global change factors.

A number of components of this analysis framework require vigorous development at this time.

- *Carbon cycle data assimilation systems.* We cannot observe all components of the terrestrial carbon cycle in all places. Terrestrial carbon cycle studies must move into the modern era of model-data syntheses and data assimilation. This will enable a variety of observational assets to be integrated into state-of-the-art, process-based models. Given the complexity of ecosystem structure and function, both multi-state data assimilation systems and mechanistically detailed terrestrial carbon cycle models are necessary. These data assimilation systems (e.g. Rayner et al., 2005; Ricciuto et al., 2008) can also be used to prioritize future observational and experimental efforts using observational system simulation experiments, and to quantify uncertainty in terrestrial ecosystem model predictions.

- *Mechanistically accurate terrestrial ecosystem carbon cycle model development.* Current terrestrial carbon cycle models are only marginally able to simulate ecosystem responses to climate, management and disturbance (Schaefer et al., 2012; Richardson et al., 2012; Raczka et al., 2013). Many processes such as disturbance, frozen soils, succession and mortality, phenology and microbial activity are crudely parameterized, limiting our ability to extrapolate fluxes and stocks across space or project them into the future. New model development is needed. Terrestrial biosphere models of the future should include accurate representation of species composition and vegetation structure; sensitivity to CO_2, nitrogen, phosphorus, and other nutrients; improved photosynthesis and respiration algorithms, including microbial processes and frozen soils; and improved links to water and energy budgets, including lateral transport of carbon and nutrients by aquatic systems. Uncertainty assessment must become a routine component of carbon cycle models. These new ecosystem models should be developed in step with our advancing capacity to observe ecosystems from space.

- *Accurate regional atmospheric inversion systems.* Atmospheric inversion systems capable of independently determining regional sources and sinks of carbon (e.g. Lauvaux et al., 2012), and including realistic assessment of atmospheric transport errors, prior flux errors, and uncertainties in atmospheric background conditions are needed.

- *Improved diagnoses and models of human contributions to the carbon cycle.* Human disturbance of the carbon cycle is a major component of the earth system. Models of anthropogenic processes that can be merged with data capturing human activity (e.g. economic data, night lights) are increasingly important to our understanding of the terrestrial carbon cycle. Models exist but are in in early stages of development. Models development and the data needed to support these models both must continue.

2.3.4 Measurement and Data Needs

- Satellite remote sensing is ideally suited to bridge the gap between global and local understanding of the terrestrial carbon cycle (Figure 2.6), and address many critical problems in terrestrial carbon cycle science. Sustained remote sensing can build the long-term observational records required to improve prognostic models of the terrestrial carbon cycle. Remote sensing systems are a key component of our current understanding of the terrestrial carbon cycle; these should be maintained. New capabilities are needed to expand our capabilities. We describe both the existing and new measurements needed to address our stated scientific objectives. These measurement systems are also articulated in Table 2.

- *Composition*: Existing measurements of land cover, land cover change, disturbance severity and type, and plant functional types are critical elements of current efforts to extend terrestrial carbon cycle models across regional to global domains, and need to be maintained.

- Existing land cover observations, however, are limited to plant functional types. While valuable, these classifications have been shown to have significant limitations in terrestrial carbon cycle science (Pavlick et al., 2012; Hilton et al, 2013) Observations of species abundance have great promise in improving extrapolation of process-based, local understanding of the terrestrial carbon cycle to regional domains, including enabling testing and validation of simulations of successional dynamics and disturbance processes across regional to global domains.

- Soil composition measurements, including soil texture, structure, chemistry, moisture and temperature are critical for understanding the terrestrial carbon cycle. Our understanding of below-ground carbon cycling is not highly developed, making precise statements of data resolution and quality requirements challenging. Soil moisture and surface temperature can be informed from remote measurements, but many soil properties must be determined from ground-based sampling and mapping. Microbial composition of soils is an area of expanding knowledge, but not at all accessible via remote sensing. The development of regional and global soil carbon data, and spatially distributed observations root structure and function are high priorities and rely heavily on in situ measurements.

- *Structure*: Reliable, large-scale observations of vegetation structure are not presently available. Remote, large-scale observations of biomass, vegetation height, and the three-dimensional structure of plant canopies would revolutionize our ability to quantify regional- to global-scale above-ground terrestrial carbon stocks and fluxes.

- Current observations of plant phenology are essential elements of current terrestrial ecosystem carbon cycle models. The temporal and spatial resolution of these observations, however, is somewhat coarse as compared to the variability in phenology in time and across species. Higher resolution observations in both space and time would enable improved fidelity in carbon cycle modeling.

- Similarly, current leaf area index observations are highly valuable and widely utilized, but limited spatial and temporal resolution and, more importantly, saturation of the sensitivity of these observations at high leaf area index, have limited the development and testing of higher fidelity modeling systems. Higher resolution leaf area measurements that do not saturate in heavily vegetated ecosystems are needed.

- *Function*: Existing remote measurements of vegetation indices and estimates of absorbed photosynthetically available radiation (APAR) provide critical input to models of ecosystem photosynthesis. A recent body of literature has demonstrated efficacy of multiangle narrow-band spectrometery for quantifying vegetation photosynthetic rate from space using Chris-Proba (see the measurements chapter). Global observations of sun-induced fluorescence, soil moisture, and leaf stress/stomatal conductance are under development and should yield substantially improved understanding of photosynthesis. Large-scale observations of leaf chemistry and health would further inform our modeling systems. The above measurements are essential to constrain photosythesis models driven by high-resolution meteorological observations and reanalyses (temperature, humidity, solar radiation).

- Respiration, as noted above, is more difficult to address via remote measurements. Ongoing in situ flux measurements (chamber, eddy covariance) are needed to complement ecosystem composition measurements related to soil and plant respiratory processes. By differencing spectral measurements of photosynthetic uptake of CO_2 and eddy covariance measurements of net primary production from tower and aircraft, respiration can be estimated directly without the need for nighttime measurements of respiration and Q_{10} models (see measurements section).

- Atmospheric carbon dioxide and methane measurements are needed to diagnose ecosystem function at regional to global scales, complementing direct observations of ecosystems (Figure 2.5). Global in situ greenhouse gas concentration and flux measurement networks, both ground- and aircraft-based, have provided the basis for our understanding of terrestrial ecosystem carbon cycling for decades and must be maintained. They provide continuity and the link for remote sensing measurements to international reference calibration standards. These data, however, have limited spatial representation, and in practice will never provide the global coverage afforded by space-based measurements. The GOSAT and recently launched OCO-2 missions are beginning to provide a more complete global picture of atmospheric CO_2 and CH_4 distributions. These satellite observation systems are pathfinders, but hold the promise of greatly improved global- to regional-scale constraint of the terrestrial carbon cycle. A global, remote measurement system for CO_2 and CH_4 with high precision, accuracy, and spatial representation should continue to be developed and implemented.

- We anticipate that the data density and coverage available through polar orbiting, passive, column-CO_2 and CH_4 satellites will be insufficient, particularly in certain regions of the globe, to bridge fully the gap in scales required to address our key regional carbon cycle science questions. Clouds obscure data collection in the high latitudes and the tropics. Passive systems cannot collect data over the nighttime earth, in particular at high latitudes during much of the year. Column observations are limited in their sensitivity to the flux-driven signals in the lower troposphere making precision requirements very stringent. Even in relatively observable regions such as the temperate mid-latitudes, satellite systems such as

> OCO-2 may not have the precision required to determine ecosystem fluxes at resolution and accuracy needed to evaluate ecosystem responses to climate variability and human management practices. Alternate instrument and observation strategies should be explored.

Higher-density, more sensitive atmospheric greenhouse gas measurements are likely needed, particularly over specific regions of the earth. These needs will become better defined as the value of data from the OCO-2 mission is explored. Higher-density regional observations could be obtained from combining orbital or suborbital, remote or in situ measurement systems. They should be maintained over time, and designed to provide daily and potentially hourly observations of CO_2 and CH_4 mole fractions, preferably weighted to the atmospheric boundary layer. Other trace gas measurements that will aid in attribution of ecosystem and anthropogenic fluxes are also needed. We recommend new, high-density, regional observational systems targeted to representative and scientifically important terrestrial ecosystems. These targeted, high-density regional atmospheric data can be merged with bottom-up observations and mechanistic models to gain important regional-scale, process-based understanding that can then be extrapolated to global domains. This regional measurement recommendation is echoed directly by the recent CEOS Strategy for Carbon Observations from Space (CEOS, 2014) which states, "The fundamental challenge is the repeat frequency, which requires a small constellation of satellites, to meet the spatial coverage requirements globally…". We echo this call for an international constellation of regional atmospheric CO_2 and CH_4 measurements.

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3.0 TECLUB measurement requirements for the next decade

A summary of the various disciplinary measurement needs are summarized in Table 2. In this final section the measurement needs are discussed in an integrated manner, with a particular focus on vegetation function and structure measurements that satisfy many of the disciplinary requirements. Technology approaches are also discussed as to how these measurements might be acquired using current satellite technology, as well as with new technology envisioned for the upcoming decade, including augmenting the existing satellite constellations to increase cloud-free acquisition frequency and the development of new types of sensors (multiangle, hyperspectral, lidar and InSAR) from both domestic and international efforts.

Table 2. Measurement requirements summary for TECLUB science priorities.

Category and attributes	Measurement	Spatial resolution	Extent	Frequency	Feasibility / maturity
Structure Variables					
Canopy height, cover, density	Lidar, Multi-spectral time series	10 m diameter waveform footprint, 10m-30m optical	Global	Semi-monthly	Mature; improvements feasible
Biomass	Lidar, radar, multi-spectral time series	10m-30m	Global	Monthly	Mature, improvements feasible
Leaf Area Index, Plant Area Index, Canopy bulk density	Lidar, interferometry, Spectroscopy, Multi-angle (e.g., MISR), multi-spectral time series	10m – 1 km	Global	Semi-monthly	Mature, improvements feasible
Veg type mapping	Multispectral time series, high-res digital (e.g., Quickbird, Worldview)	5m-30m	Global	Annual	Mature, improvements feasible
Land cover dynamics	Multispectral time series, high-res digital (Landsat, Sentinel)	30m	Global	3-4 days	Mature, improvements feasible
Function variables					
Vegetation Biochemistry Content of water, nitrogen, chlorophyll, other major pigments, lignin, and cellulose	Select wavelengths for vegetation indices, spectroscopy	Patch size dependent	Global	Bi-monthly minimum, higher frequency preferred	Feasible. Spectroscopy may require advanced data compression, band subselection

Vegetation Physiology Photosynthetic rate, light use efficiency, water use efficiency, and APAR	Time series, broad band optical, multi-angle select wavelengths for vegetation indices, spectroscopy	Ecosystem and patch size dependent	Global	Bi-monthly minimum, higher frequency preferred	Feasible. Spectroscopy may require advanced data compression, band subselection
Process Phenophases and productivity	Time series, broad band optical, select wavelengths for vegetation indices	Ecosystem and patch size dependent, 30, 250, and 500 m for continuity, higher resolution preferred for phenophases	Global	Bi-monthly minimum for phenophases, higher frequency preferred	Feasible, high spatial resolution may be difficult with frequent repeat
Composition variables					
Demographic mortality, growth, dispersion	Time series, broad band optical	30 m for continuity	Global	Annual minimum, seasonal preferred	Highly feasible and mature
Functional species/area multiplied by function, Plant Functional Type (PFT)	VSWIR Spectroscopy	Patch size dependent, 30 m for continuity	Global	Annual minimum, seasonal preferred	Feasible. May require advanced data compression, band sub-selection 30 m may be difficult with frequent repeat
Taxonomic genetic composition (species), species presence/abundance	Broad band optical, select wavelengths for vegetation indices, spectroscopy	Patch size dependent, 30 m for continuity	Global	Seasonal broad band, annual spectroscopic at peak growth season	Highly feasible & mature (broad band), spectroscopic similar to above
Soils variables					
Moisture	Microwave	SMAP			
Chemistry, texture, carbon					
Surface temperature	Surface temperature	MODIS like spatial specifications		Hourly preferred. Daily acceptable.	
Flux variables					
CO_2, CH_4, H_2O fluxes	Eddy	Global sampling of		Hourly	Very mature

	covariance, chambers	terrestrial ecosystems. Higher site density in representative terrestrial ecosystems.			
Atmospheric variables					
CO_2 and CH_4 mole fractions	In situ spectroscopy, FTIR, differential absorption lidar	1 km or finer horizontal best to avoid cloud interference. Column acceptable, but vertical resolution, especially resolution of the atmospheric boundary layer, beneficial	Global, lower density (~100 km) spacing Regional, higher density (~10 km) spacing	Global, weekly. Regional. Daily to hourly.	In situ very mature. FTIR mature. Lidar under development but feasible.

3.1 Vegetation Function

3.1.1 Vegetation Biochemistry

Plant and ecosystem processes include productivity, nutrient, carbon water and energy cycling. The content of water, nitrogen, chlorophyll and other major plant pigments, lignin, and cellulose are important determinants of vegetation function. These measurements need to be collected at medium (~30m) spatial resolution to allow assessment of spatial heterogeneity and environmental variability needed for process models of carbon and water cycling. Vegetation pigments, specifically chlorophyll a+b, and carotenoids, including xanthophylls, are the primary driver of carbon, water and energy cycling in terrestrial ecosystems. Traditionally, such pigments have mostly been derived from specific narrow band vegetation indices. However, current limitations to these observations include extraneous effects originating from variations in canopy structure and vegetation types. More recently, multi-angle spectral observations have been used to infer biochemical leaf constituents from the inversion of canopy reflectance (CR) models, which, based on radiative transfer theory and coupled with leaf optical models simulate the reflectance and the transmittance of a leaf as a function of its biochemical constituents. A number of publications have shown multi-angle, narrow-band data can be used to infer canopy light use efficiency from space across a broad range of ecosystem types (Blackburn, 2007, Hilker et al. 2011).

Imaging spectroscopy of the global land surface is a promising approach for characterizing changes in ecosystem composition and functional attributes. Hyperspectral data have demonstrated potential for measuring and assessing plant and canopy composition, biochemistry and physiology as well as ecosystem processes such as productivity. Critical measurements can be obtained via spectroscopic analysis approaches leveraging a large portion of the electromagnetic spectrum (400-2500 nm). Numerous studies have demonstrated the efficacy of airborne imaging spectroscopy for measuring several biochemical and physiological attributes including canopy water, pigments, nutrients and light use efficiency, among others (Ustin, et al. 2009, Schimel et al. 2015). The Hyperion sensor demonstrated that spaceborne imaging spectrometers have the potential to provide observations of similar functional attributes, but sensor uniformity, stability, and signal-to-noise performance limited its value in higher levels of ecosystem analysis. Although some composition and functional attributes can be measured with a few specific narrow wavebands (e.g., spectral indices related to biochemical or physiological attributes), precision and accuracy often degrade with an increase in spectral bandwidth (i.e., multispectral sampling) and a decrease in spectral resolution. Furthermore, many narrowband indices have been developed to characterize and monitor composition and functional attributes in specific ecosystems and it is ultimately unclear how transferrable such indices are between ecosystems thus adjustment and refinement may be required. Given this, it is critical that imaging spectrometers capture a large portion of the electromagnetic spectrum (e.g., 400-2500 nm) in narrow spectral wavebands.

3.1.2 Vegetation Photosynthesis

Plant photosynthetic rate, light and water use efficiency and APAR are basic measurement requirements if we are to understand vegetation carbon, water and energy cycles, their sensitivity to climate change, expected changes in the future and accompanying losses in ecosystem function.

3.1.2.1 Local and stand level requirements for vegetation photosynthesis

Recent developments in remote sensing provide, for the first time, spaceborne approaches to inferring instantaneous photosynthetic rate information to inform and constrain estimates from ecosystem process models. At the leaf level, the relationship between leaf reflectance, fluorescence and leaf carbon assimilation rate (GPP), as well as evapotranspiration, are well established (e.g. Hilker et al. 2013). The photochemical reflectance index (PRI, a narrow waveband spectral index that quantifies changes in the xanthophyll pigment cycle by comparing the reflectance at 531 nm to an insensitive reference band at 570 nm) and Solar Induced Fluorescence (SiF) are related to GPP because prior to the onset of light stress, SiF decreases as GPP increases for a fixed APAR. At the onset of light stress, PRI decreases with GPP, while SiF becomes decoupled from GPP. Hence, at the leaf level, measurements of both PRI and SiF are complementary measures of GPP. Knowing photosynthetic rate also permits improved estimates of evapotranspiration and ecosystem respiration because carbon uptake and transpiration are tightly linked.

However, at the canopy and landscape level additional complications arise. Because the light environment of canopy leaves varies widely with solar illumination angle and the ratio of incident direct to diffuse radiation, photosynthetic down-regulation varies widely with illumination angle. A further complication is that the ratio of sunlit to shaded leaves viewed by a remote sensor also varies with the relative sensor view and illumination angles; hence the fraction of light stressed to non-light stressed foliage viewed by a sensor. Multi-angle remote sensing thus provides a measure of total canopy photosynthesis that is improved relative to a single view angle.

The change in the PRI with shaded canopy fraction has been shown in a number of publications to be directly related to bulk instantaneous light use efficiency of the canopy. A significant body of literature now has shown that multi-angle measurements of canopy PRI can be used to infer the degree of reduction in canopy level LUE. When combined with remote measurements of PAR and Fpar this can be used to infer instantaneous photosynthetic rate. The relationship of fluorescence to canopy scale GPP has been demonstrated empirically from space (Frankenberg et al. 2012), and the effects of varying illumination and sensor view angles and the fraction of direct to diffuse PAR are currently an active area of research (Joiner et al. 2013, Guanter et al. 2014).

More fully establishing the use of fluorescence and PRI for canopy scale GPP will require local and stand level estimates of states and fates of the terrestrial carbon stocks, primarily focused on understanding the biophysical mechanisms governing plant carbon uptake (GPP), carbon release (respiration), evapotranspiration, and total carbon storage. Such observations have traditionally been made using eddy covariance systems and inventory measurements on the ground. While these observations will continue play an important role for modeling and monitoring of carbon fluxes, more comprehensive tools for scaling these observations is required. Variable footprint sizes and differences in how investigators infer net ecosystem exchange, GPP and respiration from eddy correlation measurements pose challenges for comparing such measurements to airborne or space based observations. Possible solutions for these challenges include near surface remote sensing, such as tower based spectral observations, which can provide data with measurement principles similar to those obtained by airborne or spaceborne sensors. At the same time linking these observations to biophysical measurements conducted in the field obtained on a continuous basis can become an essential component of existing flux tower networks. When integrated with EC measurements, these observations can serve as a ground-based validation of optical measurements as well as a tool to upscale these measurements using satellite data. This can be particularly powerful when combined with local canopy structure estimates, e.g. obtained from terrestrial laser scanning.

3.1.2.2 Regional Data Requirements for vegetation photosynthesis

Regional data requirements emerge primarily in support of the development and testing of analysis frameworks needed to quantify the magnitude and causes of regional greenhouse gas exchanges between terrestrial ecosystems and the atmosphere – whether arctic, boreal, temperate or tropical ecosystems - as well those needed to better quantify fossil fuel emissions. Differences between the global total of carbon emissions from fossil sources and land use change and uptake by the oceans indicate a terrestrial sink of 25 to 30 percent of carbon emissions (Le Quéré et al. 2014). The location and underlying mechanisms of the terrestrial sink are not well constrained. As a result, the response of this valuable ecosystem service to climate change is not well quantified. Whether the magnitude of the sink increases or decreases has important implications for climate change. The terrestrial carbon sinks likely reside in boreal/temperate or tropical ecosystems. Arctic ecosystems are more likely to be a carbon source as a result of rapid arctic tundra warming, increasing fire frequency and permafrost thaw, but these sources and sinks need to be better quantified. The analysis frameworks presented in section 2 address this need, and seek to elucidate the underlying mechanisms via (1) ecosystem carbon models that estimate carbon emissions as a function of the structure, composition and function of ecosystem vegetation and soils, and (2) atmospheric inversion models that infer the magnitude of surface – atmosphere flux from observed spatial and temporal variations in atmospheric greenhouse gas concentrations. The ecosystem and atmospheric inversion modeling approaches provide independent estimates of the ecosystem – atmosphere exchange of carbon, thus provide mutual constraints that together improve the quality of the models the underlying science.

3.1.2.3 Global Data Requirements for vegetation photosynthesis

Accurate global estimates of the terrestrial carbon cycle are the key to scientific understanding of climate feedbacks and prediction of climate scenarios. To date, terrestrial carbon feedbacks are the single most critical factor limiting the accuracy of those predictions. The lack of spatially and temporally comprehensive information results in a wide range of estimates (Friedlingstein et al. 2014), and model uncertainties are large, on the order of about ±40%. To improve upon these uncertainties, an integrated measurement framework is needed with specific data requirements at stand level, regional and global scales. Temporal measurement requirements for carbon fluxes are continuous observations at the stand level, and at least daily observations at regional and global scales, due the high variability of vegetation photosynthesis. While the spatial resolution requirements depend on patch size, at the global scale a resolution of a few hundred meters or less is highly desirable (Houghton et al. 2009. To date, no space-based mission exists that would allow routine measurement of terrestrial carbon fluxes.

Results based estimates of the vegetation xanthophyll cycle (using multi-angle PRI) and chlorophyll fluorescence (using solar induced reflectance features) show promise to overcome some of these limitations. Numerous studies have related LUE to the PRI, but the dependency of PRI on extraneous effects has hampered its use beyond the leaf and canopy scale. Recent work has shown that the status of the xanthopyll cycle may be inferred across vegetation types from multi-angle observations that can be analyzed to obtain spectra of sunlit and shaded leaves of the canopy (Hall et al., 2012). Similarly, research showing chlorophyll fluorescence can be an indicator of photosynthetic activity has allowed such retrievals from spaceborne sensors (Frankenberg et al., 2014; Joiner et al., 2013). Combination of such observations would be desired as they quantify competing energy pathways in the photosynthetic system.

3.2 Vegetation Structure

3.2.2 Vegetation height, 3D structure, biomass

While canopy height is not easily acquired from passive remote sensing systems, active sensors provide a third dimension that allows remote characterizations of ecosystem structure. Lidar data in particular provide exceptionally dense characterizations of 3D canopy structure that maintains sensitivity even in high biomass vegetation (Houghton et al, 2009, Hall et al. 2011). Estimates of canopy height as measured from lidar, greatly reduces the uncertainty associated with estimates of biomass, volume, and other vegetation structure attributes. Additional structural information is contained in the distributional shape of the canopy height profile used to summarize the distribution of lidar returns. Radar is helpful for mapping ecosystem structure at larger scales than can be currently characterized synoptically with lidar.

Wall to wall estimates of 3D vegetation structure help to ensure accurate estimates of carbon stocks but also provide a spatial context for climate change mitigation via avoided deforestation and associated co-benefits of biodiversity conservation. Such measurements and maps have been produced for the tropics but are currently not available globally. A horizontal spatial resolution of 10-30 meters or better and sub-meter vertical resolution would be highly desirable to allow linking estimates of canopy cover, height and density to remote estimates of LULCC and carbon stocks (Shugart et al. 2010). It is generally accepted and well documented that LIDAR and InSAR are the best means of measuring structure and biomass (Zolkos et al. 2013). Estimates of vegetation leaf area can also be derived from lidar, by comparing the amount of energy intercepted at a given vegetation height to the amount of energy penetrating through the ground (e.g. Whitehurst et al. 2014). Active measurements of canopy structure and LAI can be combined at global scale with 10-1000m resolution optical estimates of LAI, Plant Area Index, and canopy bulk density to improve their temporal resolution.

Systematic quantitative fusion with hyperspectral measurements is desirable to link vegetation structure with estimates of composition, nutrient and water content. Carbon stock observations (above ground) are expected to improve considerably with new spaced-based lidar missions, such as GEDI (a waveform lidar instrument planned for a future International Space Station mission), even though GEDI may only operate one year as a NASA Earth Venture Instrument mission. Other key missions currently in formulation, such as NISAR, will provide canopy vertical structure information from InSAR/radar measurements.

Future aboveground biomass mapping efforts will need to provide change through time, and even seasonal estimates to allow linking vertical structure to vegetation phenology and fuel levels for fire modeling. These efforts will also need to address carbon estimates in high latitude regions, which contains large stocks of potentially vulnerable carbon pools. At least annual observations of carbon stocks, including inferences of belowground carbon, are required to determine annual carbon gains and losses and allow accurate monitoring of climate and disturbance related changes.

Three-dimensional structural estimates will need to be complemented by remote sensing measures of LULCC (see section 2.2 and below) in order to link these changes to human sources. In addition, clumping information is desirable as it allows more comprehensive assessment of the canopy radiation regime, as well as the designation canopy gaps and individual crowns. Such observations may be obtained from high spectral resolution multi-angle observations. Furthermore, multi-story estimates (lidar/InSAR) and canopy/wetlands extent and variability (passive optical and radar) will be needed to allow the capture of seasonal cycles and changes in those cycles.

In addition to disturbance identification, quantification of biomass losses associated with disturbance can best be accomplished through combination of complementary 2D and 3D sensors. Potential existing or planned missions to address this need include not only GEDI and NISAR but also missions like TanDEM-X, which has a 4-year history (2011-2015) of data, repeating ~2-3 weeks. The potential synergies of these observations are just beginning to be explored, but the potential is enormous (Goetz and Dubayah 2011).

3.2.3 Vegetation and land cover dynamics

Land cover and land use changes play a critical role in both environmental and social contexts as the need for resources to sustain a global population that is now exceeding 7 billion people is putting pressure on remaining ecosystems, resulting in the loss of natural ecosystems and conversion of forests to agricultural lands (Foley et al., 2005). The rapidness and the scale of anthropogenic and natural changes to the environment poses challenges to the remote sensing community as comprehensive understanding of anthropogenic impacts and their feedbacks on ecosystems will require frequent and comprehensive observations across large areas, moving from simplistic representations of changes to recognition of a complex co-evolution of natural and social systems across different spatial and temporal scales. Both land cover conversions (i.e., the complete replacement of one cover type by another) and more subtle land-cover modifications and ecosystem degradation will require an integrated framework of multiple sensor operating at multiple scales. As with carbon cycle observations, a key for land cover assessment is a better integration of remote sensing and field measurements to help scale existing observations to regional and global levels.

Land cover conversion can be classified as disturbance, regeneration and permanent land cover change for instance through urban developments. Traditionally, research has focused on coarse resolution global (≥1km) and medium resolution (≈ 30m) regional observations as a result of time/space tradeoffs in satellite design. A major limitation is currently the revisit frequency of medium resolution sensors at 30m spatial resolution or higher. Virtual constellations with non-US satellites may help to facilitate the goal of 3 day revisit cycles in particular through combination with current Landsat and ESA's upcoming Sentinel-2 launch, however such combinations are limited in terms of spatial, spectral and radiometric mismatches. As a result, better coordination between sensors (Virtual constellations) and products across space agencies is needed to help improve the spatial and temporal resolution of LULCC through VC. Other major requirements include the continuation of the 40+ year Landsat record.

Current satellite estimates don't allow an accurate estimation of recovery time from disturbance as spectral vegetation indices saturate very quickly. Structural measurements are needed at Landsat-compatible (~30m) spatial resolution and with revisit frequencies of about 3 days to allow generation estimates from frequent estimates of biomass. Such measurements could also be used for validating time-integrated carbon fluxes as described in 2.3. Structural observation will need to be integrated with estimates of change in plant communities and ecosystems, through alternative stable states, to allow assessment of permanent ecosystem changes. Additional key measurements for land cover degradation and recovery from disturbance include frequent, integrated, medium resolution observations related to carbon cycle components, ecosystem processes and impacts on biodiversity. These measurements have to be frequent to allow phenological changes in vegetation to be distinguished from the effects of both pulse and press disturbances.

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