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Multi-Dimensional Forested Ecosystem Structure Requirements for Remote Sensing Observations

Kathleen Bergen, Robert G. Knox, and Sassan Saatchi, Editors

March 2006

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Final Report of the NASA Workshop:
Multi-Dimensional Forested Ecosystem Structure:
Requirements for Remote Sensing Observations
Annapolis, Maryland, June 26–28, 2003

National Aeronautics and
Space Administration

Goddard Space Flight Center
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Executive Summary

MULTI-DIMENSIONAL FORESTED ECOSYSTEM STRUCTURE: REQUIREMENTS FOR REMOTE SENSING OBSERVATIONS

Introduction

This workshop brought together two science communities—ecologists and remote sensing technologists—to help define NASA requirements for remote observations of multi-dimensional forested ecosystem structure. The workshop was designed to: clarify the key scientific goals of and requirements for remote measurements of forested ecosystem structure, identify the most relevant remote sensing technologies and their capabilities, and recommend methods by which NASA can evaluate measurement approaches using a common set of requirements. The format consisted of plenary presentations followed by breakout sessions on science (carbon/biomass, process studies, biodiversity), technology (remote sensing, models), and planning. This document summarizes the outcomes of the workshop.

Science

Biomass and carbon science and management questions and data needs include: (1) ecology (e.g., regional-global distributions and change in vegetation biomass), (2) natural resources (timber management), and (3) carbon accounting (stocks and changes in stocks). While some data exists, we currently lack spatially explicit information on biomass/carbon stocks or change for most areas of the world at useful spatial and temporal resolutions and at the desired accuracy/precision. We need to know carbon densities (Mg C/ha) with high accuracy and precision plus rates or carbon sequestration or removal. We need both spatially intensive and extensive studies, and the requirements and trade-offs need further analysis.

Process studies in ecology are concerned with canopy-level, stand, and landscape processes. For the canopy level, we need fine scale leaf area index (LAI) and LAI profile data (< 3 days and 1–3 m horizontal-vertical spatial resolution). At stand and landscape levels, we need to map disturbances plus canopy cover/LAI with 3–5 m resolution (stand) and < 30 m resolution (landscape). Relevant remote sensing products include tree heights and stem clumping (gaps), leaf area and type, and canopy vertical distribution, angles and clumping, woody biomass, stem size, number of stems, canopy nitrogen concentration, and physical environment measures that serve as common inputs to process models. Formal tests of sensor capabilities, scale dependencies, and accuracies/precision are needed. New or revised models plus visualization capabilities that can ingest remote sensing-derived parameters and capture the multi-dimensional structure and processes are important.

Biodiversity science and management is concerned with both vegetation and animal diversity at the scales of species, communities and ecosystems. Critical issues center on the fact that landscapes worldwide are rapidly changing in terms of forest composition and structure, including extinctions and invasive species, and strategic decisions are being made as to what biodiversity will be maintained on the landscape. Desired structural attributes to meet science needs include: (1) what: composition—need improvement in accuracy (from ~80 to > 90%); (2) physiognomic diversity: e.g., conifer overstory, deciduous understory, etc; how distributed: canopy cover, vertical diversity (e.g., canopy layers, foliage height diversity); (3) how much: biomass, productivity, crown volume; (4) change: phenology, disturbance. To achieve these, approaches will include: data fusion of sensor capabilities—lidar, radar, and hyperspectral / reflected optical, plus new models.

Remote Sensing

Several remote sensing techniques have strong potential to provide greater information on the three-dimensional structure of forests. Lidar has strengths in resolving height and vertical profiles, and provides indirect estimates of other attributes. Radar has strengths in estimates of forest volume, biomass, and carbon; has potential vertical profile capabilities; and is an all-weather sensor. Multi-angle sensors may provide unique information on gaps and light interception. Hyperspectral sensors have strengths in deriving parameters related to water, chlorophyll and other chemical constituents, and dry matter. Fusion of radar/lidar or other sensors with radar or lidar could augment capabilities. Currently there are varying degrees of technological and algorithm maturity. We need to eventually move from measurements to products useful for scientific and other communities. Algorithms that are directly intended to derive landscape and forest structure and composition need to be developed and refined. The robustness of these algorithms in different environmental conditions and different measurement configurations as well as scaling issues needs attention and analysis.

To best propel the technology and algorithms for the several key sensors forward, an intercomparisons approach is needed. There needs to be comparison with field data and good validation. The complementarities of sensors should be stressed, and this should lead to sensor/data fusion. The optimal blend of intensive data (sampling) and extensive data (mapping) needs to be considered. Community development should be stressed—need to think beyond just single sensors or techniques. Ultimately there should be a transition to spaceborne systems. To do this we need to define science goals, the measurement and algorithm approaches, and data products. We need to define the specific technology requirements, development strategies, pathways and timelines. We should simultaneously define processing archiving and data/products distribution. The use of existing assets for the transition process is encouraged.

Programs

Workshop sessions affirmed the need for measurements of forested ecosystem structure, using methods that provide global access and/or global sampling (depending on the application or science question). Participants also took exception to the suggestion that providing such measurements should wait until requirements are more mature. An initial set of globally consistent structure measurements would enable major qualitative advances in several key areas. Nonetheless, coordinated field programs and work to analyze and refine requirements are needed. There also was a consensus to form a working group to sustain community participation in taking the next steps. Critical areas of community involvement include: helping develop the recommended field programs, analysis and review of requirements for remote sensing observations, staying engaged with technology development for remote sensing of structure, and data fusion. Plenary discussions emphasized that this working group should aim to be international in scope and take steps to encourage participants from developing countries.

Introduction

This workshop brought together two research communities to help define NASA requirements for remote observations of multi-dimensional forested ecosystem structure: (1) scientists conducting research on the structure and function of forested ecosystems, and (2) scientists and engineers advancing methods for remote sensing of forested ecosystem structure. The workshop was designed to: clarify the key scientific goals of and requirements for remote measurements of forested ecosystem structure, identify the most relevant remote sensing technologies and their capabilities, and recommend methods by which NASA can evaluate measurement approaches using a common set of requirements. This workshop report summarizes the talks and discussions during the workshop and sets out initial findings based on those deliberations.

Science and Technology Background

There is growing recognition that some of the largest uncertainties surrounding global changes in terrestrial ecosystems are associated with understanding carbon storage in woody biomass and the effects of disturbance and recovery processes on carbon balance. Synoptic, internally consistent measures of multi-dimensional ecosystem structure that can be used to estimate above-ground biomass (and potentially total biomass) and/or quantitatively characterize disturbance impacts and recovery processes in terrestrial ecosystems would have great value in reducing these uncertainties. In addition, there are other important ecosystem attributes that are influenced by canopy structure (e.g., sustainability, biodiversity) which are receiving increasing interest from the science communities and decision makers. There is broad interest both in the functional consequences of multi-dimensional ecosystem structure and in using structure to elucidate process. Current space-based remote sensing capabilities are limited in their ability to accurately measure vegetation structure and in their sensitivity to biomass over ranges commonly found in forested ecosystems.

The workshop focused on forested ecosystems. Forested ecosystems are defined broadly here as those including a significant amount of woody vegetation with complex structure and are found in a large and important range of global biomes. These biomes include: boreal forest, temperate forest, temperate rain forest, subtropical forest, tropical rain forest, tropical dry forest, sclerophyllous woodland (Mediterranean), tropical woody savanna and woodland, and desert shrubland.

Core sensing technologies with capabilities of direct penetration of woody plant canopies and measurement of multi-dimensional structure are the active radar and lidar sensors. Radar backscatter is known to be dependent on vertical structure and biomass, and lidar sensors add the capability of canopy profiling. Both presently rely on empirical biophysical relationships to infer carbon content and dynamics from the multi-dimensional structure of vegetation. In addition, there are several other emerging technologies that offer independent, but more limited, information on vegetation structure or that may be combined (sensor fusion) with these core technologies to potentially offer a more complete characterization of forested ecosystem structure. These include, for example, hyperspectral, hyperspatial, and multi-angle imaging using solar illumination. Several extant experimental airborne radar and lidar sensors offer a variety of new measurements and more powerful approaches for estimating structure, biomass and/or quantifying disturbance and recovery processes. As a result, various overlapping concepts for possible future space-based remote sensing missions have emerged during the past four years. A strategy for proceeding, involving additional scientific study and evaluation of technological developments, is required to assess which approach(es) have the most potential to reduce major global change uncertainties. This workshop was developed to define this strategy by clearly defining science requirements, priorities, next steps for action and recommended investments.

Mission concepts emerged prior to this workshop from the Easton, MD workshop on NASA's Post-2002 mission plans [http://www.earth.nasa.gov/visions/Easton], from NASA's proposed contribution to the Climate Change Research Initiative [http://www.climatescience.gov/], and Earth Science Enterprise (ESE) program planning. These provided a useful starting point for planning, but fuller consideration of the scientific issues and requirements for ecosystem structure, biomass, and disturbance/recovery information was lacking. For example, each of the mission concepts put forward prior to this workshop might be addressed by one or more active sensors or by a combination of techniques. They all require new capabilities for measuring the structure and organization of plant canopies, for at least some of the target biomes. Because the measurements are new, exactly what levels of measurement resolution and accuracy will be needed remained unclear, as was how best to evaluate the accuracy and generality claims of alternative techniques.

This workshop was designed to review, assess, and refine the scientific requirements for remote measurement of multi-dimensional structure of forested ecosystems. Which ESE science questions are relevant? How will the data be used? Which uses are of highest priority and why? What are the accuracy, precision, scale, and resolution needs? What observations are needed most? when? where? and from what observing platforms (air- and/or space-borne)? How can the science community help guide development of the most promising technical approaches? How should alternative approaches be evaluated? What will be the evaluation criteria? What *in situ* measurements are needed for calibration and/or validation? What theoretical or model developments must occur in parallel?

To date the products of this workshop include (1) this Final Report and Executive Summary, (2) the formation of the working group Remote Sensing for Forested Ecosystem Structure, (3) a website for the Forest Structure Working Group and this Annapolis Workshop (www.foreststructure.org). The website is hosted by The University of Michigan, Ann Arbor, USA (contact: *Leland Pierce*, email: lep@umich.edu).

Objectives

The specific objectives of this workshop were:

1. Clarify the scientific goals and requirements of measurements of multi-dimensional forested ecosystem structure, in the context of national and international research priorities for reducing uncertainties about global change, especially those uncertainties associated with the Earth's carbon balance. Address three components:

- Biomass and carbon
- Process studies and inferences about processes
- Biodiversity and habitat

2. Identify the most relevant air- and spaceborne remote sensing technologies for multi-dimensional structure characterization. Analyze opportunities, limitations, and current technical challenges. Address four relevant types of technological approaches:

- Lidar and related technologies
- Radar and related technologies
- Other emerging remote sensing technologies
- Fusion of lidar/radar with other emerging remote sensing technologies

3. Review methods to evaluate measurement approaches using a common set of science requirements and suggest appropriate next steps for NASA. Identify tools to assess how proposed measurements contribute to our ability to reduce global change uncertainties. Specific topics include:

- Protocols for evaluating existing measurement approaches and technologies, e.g., tests with field data in multi-sensor airborne campaigns
- Models that relate potential measurement suites (e.g., measurements defined by a particular set of mission "measurement requirements") to their value for science (e.g., a quantifiable global change uncertainty, such as errors in estimating carbon released by land use change)
- Priorities for near term actions, activities, and investments

Schedule and Venue

The workshop took place over 2.5 days and featured a combination of plenary sessions and breakout sessions. A Monday evening session featured interactive poster presentations. The conference organizing committee invited plenary papers and other material. Interactive poster presentations were contributed. All participants participated in breakout groups and through the website collaboratory can continue to contribute to the development of workshop findings and outcomes.

Venue: The workshop was held in Annapolis, Maryland June 23–25, 2003, at the Governor Calvert Conference Center, Historic Inns of Annapolis.

Organizing Committee

Co-chairs: Robert Knox, NASA Goddard Space Flight Center, Kathleen Bergen, University of Michigan, Diane Wickland, NASA Headquarters; Committee Members: Sassan Saatchi, NASA Jet Propulsion Laboratory, Herman H. (Hank) Shugart, University of Virginia, Carolyn Hunsaker, USDA Forest Service, William (Bill) Emanuel, NASA Headquarters/ University of Virginia, and Craig Dobson, NASA Headquarters.

Summary of Invited Presentations

A successful workshop necessitated a sound understanding of the goals and its programmatic context. On the morning of day one, *Diane Wickland, NASA Headquarters and Robert Knox, NASA GSFC*, delivered the following presentations.

NASA Earth Science Enterprise (ESE) Programmatic Overview, *Diane Wickland*

Workshop Goals and Strategy, *Diane Wickland*

Introduction: Overview of Remote Sensing and Forest Structure, *Robert Knox*

Following these overviews, a series of invited plenary presentations summarized key scientific and applications themes, critical requirements, and suggested priorities.

Biomass and Carbon: *Tom Gower, University of Wisconsin*

Process Studies and Inferences about Dynamics: *Jim Clark, Duke University*

Biodiversity and Habitat: *Carolyn Hunsaker, USDA Forest Service, and Kathleen Bergen, University of Michigan*

On day two, a morning session focused on remote sensing technologies. Plenary papers provided an overview of different sensors, techniques, and capabilities.

Missions and Mission Concepts: *Craig Dobson, NASA Headquarters*

Lidar: *Ralph Dubayah, University of Maryland, and Robert Knox, NASA GSFC*

Radar: Sassan Saatchi (NASA JPL)

Other Emerging Technologies: *Jean-Luc Widlowski, Institute for Environment and Sustainability, Joint Research Center, Ispra, Italy*

Models: *Hank Shugart, University of Virginia*

Workshop Format

Breakout sessions developed the themes introduced by invited speakers and vetted a range of programmatic suggestions. The session topics were: (1) Science Goals: Biomass and Carbon, (2) Science Goals: Process Studies and Inferences about Dynamics, (3) Science Goals: Biodiversity and Habitat, (4) Remote Sensing and Structure: Radar, (5) Remote Sensing and Structure: Lidar, (6) Remote Sensing and Structure: Other Emerging Technologies, (7) Planning: Technology Needs, (8) Planning: Techniques-Based Intercomparisons, and (9) Planning: Mission Requirements.

To help structure these sessions, sets of discussion questions for each breakout group were developed by rapporteurs, working with group chairs, invited speakers, and the workshop organizing committee. Rapporteurs summarized each breakout group's findings in presentations to plenary sessions, fielding questions, and moderating related discussions. The following summaries are based on material provided by the rapporteurs and on notes provided by recorders assigned to each breakout group.

Science Goals

Biomass and Carbon

Chair: Bill Emanuel, NASA Headquarters and University of Virginia
Rapporteur: Richard Houghton, Woods Hole Research Center
Recorder: Mike Dietze, Duke University
Additional Materials: Sandra Brown, Winrock International, and Linda Heath, USDA Forest Service

Discussion

This breakout group was given the following questions for consideration: (1) What are the most compelling open science questions related to biomass and biomass carbon stocks? (2) What structural information is needed to address these questions and for related applications in carbon accounting, carbon sequestration, and timber management? (3) How will remote measurements of the multi-dimensional structure of forested ecosystems be used to address these questions and applications? (4) How do measurement requirements differ among regions or biogeographically?

1. What are the most compelling open science questions related to biomass and biomass carbon stocks?

The group proposed that the core compelling science questions come from three perspectives/fields: (a) Carbon accounting—specifically, what are the stocks of biomass/carbon, the changes in carbon stocks (sources and sinks), and the mechanisms responsible for these sources and sinks of carbon? (b) Ecology—what is the regional/global distribution of biomass? (c) Natural resources—what are the quantities of biomass for timber and paper? Forest structure data will be useful for verifying voluntary reporting of carbon projects for mitigating carbon emissions. Better data and answers to the above key questions may also help answer additional science questions, including whether carbon sinks are the result of (a) regrowth or enhanced growth, and (b) direct or indirect human effects. Moreover, they will help answer carbon management questions such as to what extent do carbon management activities reduce sources and enhance sinks and which activities give the "biggest bang for the buck" with respect to magnitude and duration of effect, and at what precision?

To date the science community has a reasonable understanding of the magnitude of forest carbon stocks in vegetation (although not necessarily spatially explicit), less so in soils, and a reasonable understanding of changes in stocks from human disturbances for certain areas of the world, (for example, the US, Canada, Scandinavian and European) countries, and some tropical counties (peninsula Malaysia and Bolivia). However, the science community is less confident in spatially explicit distributions of carbon, estimates of carbon stock change, spatial distributions of these changes, and has not determined precision of the estimates. Knowing the locations and variability of the carbon stocks and carbon stock changes is very important, and will still be important in five or fifteen years as operational measurements for "monitoring" of carbon stocks and carbon stock changes become more routine.

2. What structural information is needed to address these questions and for related applications in carbon accounting, carbon sequestration, and timber management?

In terms of data needed, it is important to know carbon densities (Mg C/ha) with high accuracy and precision. Total carbon is important, however, component measures of biomass/carbon are also needed: height, crown cover, basal area and density. Rates of carbon sequestration and rates of change/disturbance are also important.

Two measurement approaches are possible: wall-to-wall and sampling. In the case of sampling, ***repeated measurement at permanent plots*** gains a factor of 10 in precision over random sampling at multiple dates and is strongly recommended. Applying the "permanent plot" concept used in ground studies to remote sensing applications could reduce uncertainty (i.e., increase precision). That is, subtracting carbon stocks at two different times will produce more precise estimates of change if the remote sensing data are exactly matched in terms of location. Both intensive case studies and then spatial extrapolations of these are needed. The particular appropriate or required spatial and temporal scales will depend upon the question being addressed, and these need careful, systematic analysis. Wall-to-wall requires determination of the most effective sensors, spatial resolutions, and measurement precisions. Comparisons will be useful: defining the accuracies and precision needed probably require a number of attempts, each one based on an alternative approach. For example, one approach might start with the current understanding of regional distributions of sources and sinks of carbon available from a comparison of different methods (forest inventories, atmospheric inverse, land-use, sampled and wall-to-wall remote sensing, etc.).

3. How will remote measurements of the multi-dimensional structure of forested ecosystems be used to address these questions?

Remote sensing measures may either provide an estimate of total biomass/carbon directly (e.g., inversion of radar data), or provide component measures of biomass/carbon that may be used together with allometric equations to estimate biomass/carbon. In terms of "how to" the group stresses that in the second case, using remote sensing to fit plot-level biomass data derived from allometric equations that are based on DBH provides an "estimate" of biomass rather than a direct measurement. In addition to height, crown cover or basal area is needed to estimate biomass, or the number of stems and DBH are needed. Height data alone are not enough to address the causes of biomass change; also needed is something about age or productivity class (to distinguish between young forests on rich sites (high rates of growth) from old forests on poor sites (low rates of growth). With biomass allometry remaining a significant source of uncertainty, an optimistic possibility is that perhaps remote sensing will generate indirect data that replace allometric regressions.

a. Biomass for carbon accounting: In the United States, the Forest Inventory and Analysis (FIA) field data allow for good aboveground estimates based on a rich set of historic and current surveys, but data collection is "expensive", and not wall-to-wall. The FIA program currently uses optical imagery (aerial photography) in the first phase of its survey. There might be more cost-effective ways for estimating carbon stocks/volumes to replace such extensive fieldwork; however, this topic would need to be addressed cooperatively with the FIA program. There is also a need to supplement the systematic measurements of living biomass measurements made by the FIA with measurements of: (1) below-ground biomass, (2) biomass in non-forest ecosystems (e.g., woody encroachment), and (3) biomass in lower productivity forest lands (not traditionally surveyed through FIA). The group suggested that perhaps NASA could help persuade other agencies to contribute to these additional issues, and/or itself support more measurements below ground and in non-forest woody vegetation in the U.S., as well as measurements in other biomes. In both cases—providing enhancement to the current FIA measurement program and supplementing its scope, the groundwork needs to be done in a systematic way.
b. For ecology carbon applications: same as for above, but at finer resolution and probably higher precision. For example, crown areas per tree, tree heights, plant functional types and/or species groups (e.g., selection of hardwood species groups) to match allometry databases. New allometric models are needed to better match with the structural data from remote sensing—e.g., biomass as a function of tree height or tree crown or a combination of both but not based on DBH as is currently used.
c. For natural resources management: To be relevant for the full range of conditions, forest structure work needs to be tested on disturbed areas, particularly of different types of harvests (such as selective cutting, group selection, etc), wildfire intensities, land clearing intensities, and insect- and disease-induced mortality. (Note that the final structure resulting from different disturbances may be very similar).

4. How do measurement requirements differ among regions or biogeographically?

There are some generally consistent relationships relating biomass and biomass carbon to simple structural metrics, but these have not been rigorously parameterized. (Probably best constrained for temperate forests.) Landscape-level studies are needed to address the scaling and test scaling methods. The required scale and resolution will vary across biomes.

Recommendations

- The most compelling science and applications questions relate to: (1) locations/spatial distributions and variability of biomass/carbon stocks plus magnitude and direction of changes in biomass/carbon stocks for carbon accounting; (2) biomass/carbon for timber management; and (3) ecological understanding of causes and dynamics of biomass/carbon (including causes of change in carbon stocks). Also important is the uncertainty of estimates.
- Biomass can be estimated from structure: need height plus some measure of cover (cover/basal area/crown volume). Traditional ground-based approach uses numbers of stems and DBH, with allometric equations. Will need new allometric models to better match with the structural data from remote sensing. Explore the option that remote

sensing can generate data that replaces allometric equations and/or generates direct estimates.

- Need to consider sampling (adequate for statistical summaries) and wall-to-wall (for spatially explicit and variability measures) approaches.
- In sampling with remote sensing to measure changes, uncertainty might be reduced using repeated measurements at the same precision locations (cf. ~10X improvement from repeated ground measurements at permanent plots instead of random sampling at multiple dates). This requires better geolocation than has been customary.
- Need to supplement systematic measurements of living aboveground biomass/volume in trees with better data on belowground biomass, biomass in non-forest ecosystems/lower productivity lands, and variation in wood density.
- Need both spatially intensive and extensive measurements and studies. Trade-offs need analysis. Defining appropriate accuracies and precision require more than one approach (not just sources and sinks from atmospheric inverse, forest inventories, etc.), starting from different perspectives.

Process Studies and Inferences about Dynamics

Chair: Hank Shugart, University of Virginia
Rapporteur: David Ellsworth, University of Michigan
Recorder: Mike Wolosin, Duke University

Discussion

This group considered the following questions: What ecological processes are most relevant to understanding terrestrial C cycles, N and other nutrient cycles, and hydrological cycles? What spatial and temporal scales are most key to remote sensing of these processes? What measurements are most pressing to facilitate process-level modeling at different geographic scales?

1. What ecological processes are most relevant to understanding terrestrial C cycles, N and other nutrient cycles, and hydrological cycles?

Multi-level forest structural data is needed for process-level studies and modeling efforts most relevant to understanding terrestrial ecosystem processes, including physiological, biogeochemical, and demographic processes. The interest in ecosystem processes is broadly determined by national needs in terms of understanding natural and anthropogenic environmental change effects on ecosystem functioning (including separating effects of the former from those of the latter). Moreover, these changes may have significant effects on future forest structure and function. Fundamental questions on the implications of spatial and interannual variation in ecosystem functioning for short- and long-term ecosystem carbon cycles, nutrient cycles and hydrological cycles are addressed by research in this area.

Canopy-level processes are critical to resolve, particularly for understanding regulation of CO_2 exchange of multi-dimensional forest ecosystem processes. Structural data are useful in resolving these processes. The key canopy processes of interest include photosynthesis, respiration (by ecosystem components), transpiration, and indirectly, decomposition and N mineralization.

In addition to the physiological processes central to ecosystem C and N cycles, there are also a set of longer-term successional processes that are important from the stand-point of longer-term disturbance effects on ecosystems, including the processes central to stand recovery after partial or catastrophic disturbances (both natural and human-induced). Major disturbances of interest from a landscape C balance perspective include fires, management and other human-driven modifications, and insect and disease outbreaks as key triggers that can lead to landscape-level C losses, stand initiation, and large-scale species changes. Often variation associated with these disturbances can result from partial rather than complete destruction of the dominant species components of the ecosystem. Here, processes of interest include individual/stand level processes like growth, mortality, and species dispersal/migration. Ultimately, these processes will be important to the structure/composition and functioning of forest ecosystems many decades from now, and multiple scales are of interest to resolve.

2. What measurements are most pressing to facilitate process-level modeling at different geographic scales?

3. What spatial and temporal scales are most key to remote sensing of these processes?

At the canopy scale, given the key role of leaf area index and its vertical profile in regulating these ecosystem processes, there is a strong need for fine spatial scale leaf area index (LAI) and LAI profile data. The necessary spatial resolution and extent is important to determine. For tree canopy and crown processes, frequent (< 3 d) return times allow for resolution of canopy phenology, an important control on overall ecosystem CO_2 fluxes. Also, because crowns of dominant forest trees can have a diameter in the range of 10–15 m, a 1–3 m horizontal spatial resolution will be key for resolving individual tree crowns and associated tree crown processes (including photosynthesis and biomass growth but also mortality and gap formation. Formal tests of scale dependencies of various estimates are needed.

At the larger or landscape scale, seasonal data with the capability of identifying and mapping key disturbances such as fire and logging, with 3–5 m resolution are needed. The spatial resolution must be sufficient to detect single tree-falls, in an ensemble type of manner. Large area coverage is necessary for things like fire—at landscape scale. The extensive dataset that is envisaged might capture mean canopy cover/LAI at spatial scales < 30 m, as well as variance and moments, to enable the recovery of statistical representations of the disturbance processes. Coarser grid-level information for modeling should involve storing means and statistics at sub-grid level.

A "short list" of desired remote sensing products relevant to process-level studies include tree heights and stem clumping (gaps), leaf area and type, and canopy vertical distribution, angles and clumping, woody biomass, stem size, number of stems, canopy nitrogen concentration, and physical environment measures that serve as common inputs to process models.

Recommendations

- To resolve canopy-level processes, there is a strong need for fine spatial scale leaf distribution (e.g., LAI) and LAI profile data. Frequent (< 3 days) and sufficiently detailed 1–3 m horizontal spatial resolution is needed to resolve individual tree crowns.
- Processes central to stand recovery after partial or catastrophic disturbances (both natural and human-induced) require seasonal data to identify and map key disturbances such as fire and logging, and disturbance responses, with 3–5 m resolution. Large area coverage is necessary for disturbances like fire. The extensive dataset that is envisaged might capture mean canopy cover/LAI at spatial scales < 30 m, as well as variance and moments, to enable the recovery of statistical representations of the disturbance processes.
- Formal tests of scale dependencies of various estimates are needed.
- A "short list" of desired remote sensing products relevant to process-level studies that included: tree heights and stem clumping (gaps), leaf area and type, and its vertical distribution, angles and clumping, woody biomass, stem size, number of stems, canopy nitrogen concentration, and physical environment measures that serve as common inputs to process models.

Biodiversity and Habitat

Chair: Carolyn Hunsaker, USDA Forest Service
Rapporteur: John Weishampel, University of Central Florida
Recorder: Peter Hyde, University of Maryland

Discussion

Several discussion questions were distributed to the biodiversity/habitat breakout group: (1) What structural information is needed for biodiversity (multiple species) science? (2) What structural information is needed for habitat (single species) science and management? (3) How do measurement requirements differ among regions or biogeographically? (4) What are the most compelling open science and management questions relation to biodiversity and habitat?

1. What structural information is needed for biodiversity (multiple species) science?

2. What structural information is needed for habitat (single species) science and management?

The group considered both of these questions together. The needs for remote sensing of structure for biodiversity and habitat have been previously considered primarily by wildlife managers interested in using remote sensing derived environmental variables. Core variables most highly desired from the California Department of Fish and Game was given as an example: (1) tree height, (2) canopy closure, (3) tree species composition, and (4) canopy strata. A more comprehensive group of attributes was derived at the Lake Tahoe 1999 USDA Forest Service meeting. These were: canopy cover, life form, large tree density, tree height, tree crown diameter, biomass, crown volume, height to live crown, tree decadence, surface dead, soil moisture, foliar moisture, vertical diversity. However, current structural metrics used by wildlife professionals are largely limited to what is readily available which at the maximum includes: (1) tree height, (2) cover, and (3) species composition. Furthermore, it is important to note that even data on these variables may presently be limited primarily to lands under certain jurisdictions and land management agencies, their spatial extent is limited because they are acquired from field surveys or large-scale aerial photography. Moreover, they may not be consistent between different areas or agencies. In addition to the metrics identified by wildlife and land managers prior to this workshop, the following were identified at the workshop as valuable and as potentially retrievable from remote sensing: understory processes (drainage, fire, edaphic conditions, flooding), time series (semi-monthly to monthly), proxies for disturbance, productivity, vertical profiles to map interstitial species, abiotic factors (temperature, precipitation, humidity), proxies for successional stages.

3. How do measurement requirements differ, including among regions or biogeographically, but also by scientific question?

4. What are the most compelling open science and management questions relation to biodiversity and habitat?

While the structural variables for both biodiversity (multiple species) and habitat (single species) were discussed together, the group noted that specialized metrics are needed for different types of diversity, single species vs. multiple species diversity, rare species, invasive species, tropics vs. temperate/boreal vs. savanna, functional vs. compositional diversity vs. complexity. These may use the same structural information, but can use it in different ways. At the simplest, these are “metrics”, as they become more complex they may become “models”.

In terms of future scientific research: large uncertainties in biodiversity knowledge (e.g., biodiversity hotspots or habitat requirements) exist while some of these uncertainties must reduced before structural correlates can be found at the same time, better structural information is needed to study them. What is known is that biodiversity and habitat are changing rapidly as a result of both human and natural disturbance (land-cover change, fire, climate change, etc.).

Solutions include multi-sensor fusion, targeting disturbed or sensitive areas with one sensor for intensive investigation with other tools (“sensor web”), matching sensor/metrics to the problem: one size does not fit all, create composite vertical and horizontal metrics. To do this a combination of radar, lidar, and VNIR/ hyperspectral is needed. The radar and lidar will provide the capability to get the vertical and the VNIR/ hyperspectral primarily the horizontal. Of these radar and lidar are the least available and therefore, the greater need for development. Accuracy is application-dependent. Accuracy requirements are often unknown. Prioritizing metrics is important but challenging to accomplish with a diversity of user interests.

Recommendations

- Biodiversity structural information needs:
  (1) include both vegetation diversity and animal diversity habitat requirements, (2) occur over scales of biodiversity of species, communities and ecosystems, (3) are important because landscapes worldwide are rapidly changing in terms of forest composition and structure (e.g., harvesting, regrowth, conversion, invasive species, etc.) and real strategic decisions are being made as to which land areas and species should or will be maintained on the landscape.
- The desired structural attributes to meet these science needs are: (1) vegetation species or community composition—improvement in accuracy (from ~80 to > 90%), (2) physiognomic diversity of forest canopies, e.g., (conifer overstory, deciduous understory, etc. (3) how distributed—including horizontal (canopy cover) and vertical (e.g., vertical profile, canopy layers, foliage height diversity), (4) how much—biomass, productivity, crown volume, and (5) change—phenology and disturbance, both horizontal and vertical.
- The overall approaches that the group believed would best meet these needs are a fusion of sensor capabilities will be advantageous to retrieve these desired parameters, These are lidar, radar, and hyperspectral. Radar and lidar are less available, currently so may need emphasis to “catch” up. Fine and medium spatial resolution needed.
- Along with developing the remote sensing capabilities in radar/lidar, a new generation of biodiversity and habitat metrics and models should be developed that incorporate multi-dimensional structure and at different resolutions and using remote sensing-derived inputs.

Remote Sensing and Structure

Radar

Chair: Craig Dobson, NASA Headquarters
Rapporteur: Jon Ranson, NASA GSFC
Recorder: Wayne Walker, University of Michigan

Discussion

The radar group considered the following questions: (1) What are the most compelling results in radar measurements of structure and biomass? (2) What are the most important features of radar techniques for addressing forest structure and biomass? (3) What are the existing and future radar technologies for addressing forest structure and biomass requirements?

1. What are the most compelling results in radar measurements of structure and biomass?

Both horizontal and vertical information are available from radar. In terms of direct information, this includes heights (at meter(s) level accuracy), and surface topography. In terms of indirect information, radar provides biomass estimates that are related to stand basal area and volume. Measurement results for tropical systems currently are more limited than for temperate and boreal. Radar sensitivity to structure is primarily to the live above ground tree components. The standing and forest floor dead trees do not impact the radar measurements. Radar also shows sensitivity to foliage moisture, and there is some sensitivity to surface moisture under more open canopies. Radar can also discern standing water under forest canopies and thus provide structure and biomass of floodplain forests.

2. What are the most important features of radar techniques for addressing forest structure and biomass?

Radar is an imager—while current lidar capability is primarily a sampler. Radar provides the spatially continuous mapping and measurement capabilities. Radar has greater canopy penetration and volume sampling than any other sensor. Measurements at low frequencies or longer wavelengths such as UHF (P-band) with 70 cm wavelength and VHF at meters wavelengths provide the most direct measurements of stem volume. Airborne measurements with these instruments have provided ample results to assess the system requirements, measurement accuracies and limitations. For example, results over northern hemisphere, boreal and temperate forests show a strong sensitivity of P-band polarimetric measurement to above ground live volume or biomass. In tropical forests, on the other hand, the assessment of P-band performance is not possible because of the lack of measurements. However, limited data indicates that P-band sensitivity to forest structure is good though slightly less sensitive than temperate forests. At these frequencies, information about leaves cannot be discerned unless in dense tropical systems. High spatial resolutions with pixel size of several meters are possible and being an active sensor at radio frequencies, radar has stem mapping capabilities with lower frequencies and high resolution. Radar is an all-time all-weather sensor. This capability will allow the use of radar for robust mapping of changes in forest cover due to deforestation and disturbance as major elements of balancing the terrestrial carbon budget.

3. What are the existing and future radar technologies for addressing forest structure and biomass requirements?

To meet forest structure and biomass measurement requirements we need low frequency and polarimetry capabilities in radars. Availability of multi-frequency sensors can improve forest biomass estimation and separating structural components such as the branch and foliage layers. Interferometric SAR (InSAR) measurements are particularly suitable for estimating forest height with meters accuracy and combination of polarimetry and interferometry can further improve estimation of three-dimensional forest structure. However, further research and measurements are needed to establish the required configuration and performance of such advance systems for spaceborne applications. Suborbital radar systems operating at different frequencies and modes can provide the best means to resolve performance and algorithm issues.

Existing and future non-US radar missions can also be explored to assess the use and applications of the radar configurations for forest structure science. For example, in the near future the Japanese ALOS system should provide dual and polarimetric data that can be used for structural estimations in areas with low forest density. ALOS may also provide some zero-baseline interferometry data that can be used in conjunction with the polarimetric data to test new approaches for forest height estimation.

Recommendations

- Need SARs operating at low frequency (e.g., P-band) with polarimetric capabilities. The technology for such systems is mature and the current-state-of-art suggests high sensitivity (high measurement accuracy) to forest volume and biomass in northern latitudes and slightly lower sensitivity in areas of dense tropical forests.

- Need interferometric SAR capabilities for forest height measurements. The best configuration for tree height estimation and accuracy are not established. Interferometric measurements can be performed at L-band and possibly P-band. More work is needed to address s all technological and measurement capabilities.
- Focus initial SAR efforts on forest volume, biomass, and height measurements—radar can do this over large geographic regions (spatially continuous imager) and in all weather and illumination conditions—consistent and reliable source of measurement and monitoring.
- Investigate both spaceborne and sub-orbital programs
- Invest in algorithm development and develop more robust biophysically based models
- Cooperate with other non-US SAR programs, while at the same time recognizing that their sensors are not ideal for forest structure science and applications, so a better solution is imperative to work towards here at home.

Lidar

Chair: Robert Knox, NASA GSFC
Rapporteur: Michael Lefsky, Colorado State University
Recorder: Birgit Peterson, University of Maryland

Discussion

The lidar group considered the following questions: (1) What are the most compelling results in lidar measurement of ecosystem structure? (2) What potentially confounding signals affect different lidar systems? How can they be controlled in system design or data analysis? (3) Are there ways to overcome the practical and/or intrinsic limitations of lidar for remote sensing of structure? (4) What lidar data will be available from commercial remote sensing firms and how can NASA funded researchers work with the NCALM initiative?

1. What are the most compelling results in lidar measurement of ecosystem structure?

The group first considered what direct vs. indirect measures may be made and how well lidar has done. Direct measures include: height, canopy topography, intercepted surfaces, canopy closure (with reflectance correction), and canopy volume. In terms of height (the only one of these discussed): (a) There are drawbacks to both waveform sampling and discrete return lidar in short stature systems. (b) There are limits to the upper-boundary sensitivity of all lidar systems. Crown shape is a factor, but we are confident that 1 m accuracy from space is possible. (c) Ground surface elevation can be difficult in high closure situations, although spatial processing of elevation can address that. (d) A question remains on height remeasurement—what is the minimum increment that we can see, what is the corresponding temporal resolution needed for that increment? (e) Overall, lidar is excellent for measuring height.

Indirect measures include: DBH, successional status, aboveground biomass, distribution of canopy structure, canopy volume and light transmittance, and aboveground productivity. DBH: is DBH intrinsically better than height as a tree and plot level variable? DBH is better predictor of volume at the individual level, while height is a very good indicator of volume at a plot scale. There has been some work on mean, stdev of DBH. Biomass/carbon: Lidar has strong potential to measure biomass, however, there is a pressing need for inter-biome and inter-sensor comparisons—how variable are these relationships across and within biomes—evidence exists to support, but more much research is needed. We recognize the need to work in uniformly high-biomass systems to see if we get adequate resolution. For retrieving biomass, lidar is relatively easy to process, and most approaches work well, but we need to move from empirical to theory based modeling approaches. Scaling concerns are still raised when processing field data vs. lidar. For process studies, tests of our ability to measure difference in height are needed to estimate changes in biomass. For biodiversity and habitat studies lidar should be able to contribute to a number of variables: canopy cover, life form diversity (If lifeforms have different height or different profile distribution), large tree density, tree size, vertical diversity, biomass, crown volume, height to live crown, snags, possibly others through inference. Live to dead biomass ratio- requires two colors. Mean Annual Increment of woody biomass is a strong possibility with positive initial results. Lidar may not be appropriate for soil moisture or surface dead material. In terms of whether the results are biome specific: Although the structures sensed by lidar systems are remarkably diverse, there is preliminary evidence that cross-site, cross composition, and even cross biome comparisons can be successful, which should be interpreted to mean that the hypothesis that such relationships exist should be studied

2. What potentially confounding signals affect different lidar systems? How can they be controlled in system design or data analysis?

The potentially confounding signals for lidar are: clouds, slope/ground roughness, buildings/boulders/ pits, and seasonal/diurnal variation. Technology development is need to improve imaging capabilities for airborne and spaceborne systems, but sampling with lidar may be adequate for global carbon questions and many other problems. Data fusion (with multi-angle or radar data) may address this problem. The most confounding problem is the availability of data. Commercial data is largely limited to first world regions and overall quality and quantity of data needs to be carefully monitored.

3. Are there ways to overcome the practical and/or intrinsic limitations of lidar for remote sensing of structure?

One inherent limitation is that lidar cannot penetrate leaves, while radar can. Thus, synergism/fusion with other instruments (such as radar) should address confounding signals or resolve limitations of lidar measurements of forest structure; however, fusion of the basic measurements is still a research problem. A field experiment focused on a cross-site comparison between different instruments (lidar, radar, optical) and different estimation methods should b be one of the next steps. There is a need to develop true biophysically based models.

4. What lidar data will be available from commercial remote sensing firms? How can NASA funded researchers work with the NCALM initiative?

Problems include the lack of characterization of commercial devices and commercial operators. NCALM is well characterized and has excellent operators, but requires NSF funding. Acquiring one or more LVIS clones as facility instruments is one possibility that would allow comparison of commercial data to a very well characterized instrument.

Recommendations

- Lidar is excellent for measuring height of the forest canopy, currently transects.
- Lidar may be the best type of sensor for canopy profiles.
- Lidar can estimate biomass; however, there is a need for inter-sensor comparisons and inter-biome comparisons, as well as tests of resolution in uniformly high-biomass systems. Need to test ability to measure difference in height with re-measurement to estimate changes in biomass.
- Lidar can meet the varied biodiversity requirements: canopy cover, life form diversity, tree size, vertical diversity, biomass, height to live crown, snags, etc.
- A field experiment, focused on a cross-site comparison between different instruments (lidar, radar, optical) and different estimation methods is one of the appropriate next steps.
- Need to develop biophysically based models, currently only have empirical models.

Other Emerging Technologies

Chair: Hank Shugart, University of Virginia
Rapporteur: Susan Ustin, University of California Davis
Recorder: Mike Wolosin, Duke University

Discussion

This group discussed the following questions related to hyperspectral sensors, high-resolution sensors, multi-angle sensors, and other emerging technologies: (1) What structural measurements can be made with other emerging remote sensing technologies? (2) What are the advantages of multi-angle observations? (3) What are the advantages of hyperspectral data? (4) What are the advantages of high-resolution data? (5) What are the advantages of flying satellite constellations and synergies with other instruments? (6) What are other emerging technologies and what could they provide? (7) Are there limitations in current technology to measuring structure with other emerging technologies? Are there demonstrated (medium Technology Readiness Level or TRL) or new (low TRL) ways to overcome those limitations?

1. What structural measurements can be made with other emerging remote sensing technologies?

This group focused on capabilities of multi-angle and hyperspectral sensors (and in synergy with lidar and/or radar) in support of answering the questions: what structural measurements can be made with other remote sensing technologies? We addressed the question of what measurements are direct and which are indirect for each of the technologies.

2. What are the advantages of multi-angle observations?

Multiple view angle imagers (e.g., MISR, POLDER instruments) provide multi-spectral imaging at multiple view angles. This provides data that in inverse radiative transfer models can be processed to provide quantitative estimates of leaf area index and leaf angle distribution; two forest structure properties used in ecosystem production models. The combination of multispectral view angle data can yield improved forest land cover characterization including estimates of landscape mosaics, gaps, vegetation functional types and flooded forest land (using specular reflectance). The data would benefit by combination with lidar/radar for tree height. Increased spatial resolution (~100 m) and selection of view angles specifically for canopy structure and inversion models would provide better structure information than current generation satellites. A current disadvantage to multi-angle imagers is that few researchers have had access to data characterizing bidirectional reflectance distribution functions (BRDF) and field and lab goniometers are not generally available. As a result, the science of using multiband spectral BRDF data needs more research to fully develop applications.

3. What are the advantages of hyperspectral data?

Hyperspectral imagers (e.g., AVIRIS, Hyperion instruments) are instruments that have contiguous narrow spectral bands across the visible and reflected solar infrared wavelength region. Typically, 200+ 10 nm bands represent current technical capabilities with instruments having 1000:1 SNR in the VNIR and 500:1 SNR in the shortwave infrared are considered necessary to meet science objectives. Mature designs exist that indicate that the number of spectral bands could be doubled if science drivers were identified. The usual mode of operation is in the nadir direction but the instruments could be operated in multiple view angle modes. The EU is considering building a multiple view angle hyperspectral imager (SPECTRA) with some of these features in the 2008 time frame.

Hyperspectral instruments are unique in making direct measurements of chemical properties of the atmosphere (water vapor, CO_2, etc.), and surface conditions including vegetation (chlorophyll, water, dry matter [ligno-cellulose]) The spectral information in hyperspectral imagers provides the most detailed information for land cover characterization. This is of direct relevance for species/community mapping within physiognomic types and can provide enhanced information for mapping invasive species and rare/endangered species.

Hyperspectral imagers are unique in being able to directly measure properties related to physiological processes and detection to plant stresses. The spectral detail in the VNIR allows separation of chlorophyll concentrations and LAI based on modeling of the red-edge (i.e., the long wavelength edge of the chlorophyll absorption feature). Further, because water absorbs less strongly than plant photosynthetic pigments, the water absorption penetrates deeper in the canopy and this provides an alternative to vegetation indices based on chlorophyll absorption for estimating LAI. This is an important technology enhancement since NDVI type measures saturate at LAIs > 3–4 while water indices do not saturate until near 10 or greater. The conifer forests of the Pacific Northwest are noted for having the highest known LAIs (up to ~12), suggesting that the full global range of LAIs can be estimated through this measurement.

Because water and dry matter can be directly measured, it is possible to make estimates of living and dead vegetation (e.g., coarse woody debris and plant litter). For woody semi-arid shrub and savanna biomes where aboveground biomass is low (e.g., <50 Mg/ha) and of low statue, hyperspectral instruments may provide the best way to retrieve biomass. The low stature and low biomass may make these systems less sensitive to lidar and radar instruments. Because approximately 40% of the terrestrial land cover falls into these ecosystem types and such systems are known to be highly sensitive to climate change, there is a high priority for developing this capability. It has been suggested that semi-arid systems also are potential sources for release of non-organic carbon compounds such as carbonates and hyperspectral imagers have potential to provide information on carbonates also.

There is obvious synergy with lidar and or radar profilers. Most researchers have suggested that 30 m pixel resolution (matching Landsat TM and Hyperion) or better is desired but no systematic analysis of spatial requirements has been done. To increase spatial coverage either multiple instruments on different platform configurations are needed or improved large focal plane arrays. New designs have reduced size and power requirements that will reduce cost of previous instruments. Disadvantages are high data rates for frequent global coverage or for multiple view angle concepts. There is a perception at NASA that the commercial sector will build and operate this technology but no commercial vendors are currently planning an instrument and all previous commercial instruments have been discontinued. The reluctance of the commercial sector to support a Landsat follow-on instrument (the LDCM mission), a more commercially mature technology, should demonstrate the lack of a commercial base for hyperspectral technology.

4. What are the advantages of high-resolution data?

High-resolution data include those from high spatial resolution multispectral imagers (e.g., Ikonos, Quickbird, SPOT). In contrast to hyperspectral and SAR instruments, the commercial sector is actively building and operating satellites in the sub–5 m pixel range. This technology can provide data of photogrammetric quality and stereo images from space platforms. This can provide detailed information on canopy structure, tree spacing, gap structures, etc. The instruments have potential synergy with lidar/radar and hyperspectral imagers. Some challenges are that commercial instruments may not meet scientific data requirements because of concerns about spectral calibration and stability and infrequent revisit cycle for nadir viewing. High spatial resolution instruments provide scientific challenges for interpreting spectral information based on path scattering from adjacent pixels. Further, base maps for many parts of the earth are not available and registration of the data to geographic coordinates may not allow accurate pixel location.

5. What are the advantages of flying satellite constellations and synergies with other instruments?

Constellation and formation flying would provide a mechanism for more frequent coverage when using high spatial resolution systems such as expected for deploying the technologies described above. Multiple platforms would provide another basis for acquiring BRDF or stereo viewing information if overpass times or view angles are different.

It is strongly recommended that field evaluations in multiple biome types be conducted to evaluate the synergistic use of hyperspectral, multiple view angle, lidar, radar, high spatial resolution, and multiband thermal instruments. Airborne instruments exist for each of these technologies. Research issues include spatial scales, spectral bands and band placements, view angles, vertical resolution, polarization. Finally, additional research is needed to understand possible data fusion issues (e.g., can low spatial resolution-high temporal resolution instruments be combined with high spatial-low temporal resolution instruments to achieve science goals).

6. What are other emerging technologies and what could they provide?

There are several: (a) Polarization multispectral capabilities (e.g., POLDER) may improve structure detection. (b) Fluorescence (e.g., EPA imagers) provides information on plant physiology and stresses; technologies can use Fraunhoeffer lines (where no incoming solar radiation exists) or active lidar sensing. (c) Multiband thermal imagers may be used to detect plant stress (elevated canopy temperatures), possibly discriminate coarse woody debris (CWD), and discriminate different minerals based on gray body emittances.

7. Are there limitations in current technology to measuring structure with other emerging technologies? Are there demonstrated (medium TRL) or new (low TRL) ways to overcome those limitations?

All of the technologies identified have acceptable TRL (> 6). All have prototype airborne instruments and most/all have had some level of technology demonstration in other space instruments.

Recommendations

- Multi-angle sensors may provide quantitative estimates of leaf area index and leaf angle distribution; two properties used in ecosystem production models.
- The science of using multiband spectral BRDF data needs more research to fully develop applications.
- Structure variables for which hyperspectral may be advantageous include leaf area index, estimates of living and dead vegetation (e.g., coarse woody debris and plant litter), and biomass in woody semi-arid shrub and savanna biomes where aboveground biomass is low (e.g., < 50 Mg/ha) and of low stature, which may make radar and lidar biomass measurements more difficult.
- High spatial resolution sensors can provide data of photogrammetric quality and stereo images from space platforms plus detailed information on canopy structure, tree spacing, gap structures, etc.
- Strongly recommend field evaluations in multiple biome types to be conducted to evaluate the synergistic use of hyperspectral, multiple view angle, lidar, radar, and high spatial resolution. Research issues to include spatial scales, spectral bands and band placements, view angles, vertical resolution, polarization, and possible data fusion issues.

Planning

Because the Forest Structure Workshop must combine (1) the science goals and (2) the available technologies and transform these to developing a science and technology plan, breakout sessions were scheduled to address this.

Technology Needs

Chair: Sassan Saatchi, NASA JPL
Rapporteur: Jan Gervin, NASA GSFC
Recorder: Birgit Peterson, University of Maryland

Discussion

This group examined the technology needs for remote sensing of forested ecosystem structure and related issues. The group separated the requirements into spaceborne and airborne sensing requirements by instrument and into supporting technologies needed to make the measurements and interpretation of the data viable.

1. Lidar: The group identified three main areas of technology development for the spaceborne lidars. The highest priority item is to have reliable, sustained (5 year mission lifetime) high repetition rate (> 300 shots/s). Two-color laser (e.g., 1064 and 532 nm) development is highly desired for any vegetation structure mission. Lasers with variable spot sizes as small as 10 to 25 m were identified as highly desirable. In order to reduce the required laser output power, it was recommended that heterodyne quantum noise limited detectors be developed for space-based lidars. A multi-angle lidar with an angle separation greater than 20° would provide valuable data on light penetration into the canopy. It was recommended that an airborne sensing prototype for this sensor might be developed possibly as part of an IIP demonstration.

2. Radar: Three types of radars have potential to measure vegetation structure information. Each type of radar provides different structure information. The three types of radar are polarimetric low frequency (UHF and VHF) radars, high frequency (X-band or C-band) interferometric radar (optionally with a multiple baselines) and polarimetric interferometric radar (L-band). These systems are at different levels of technology maturity for spaceborne deployment. Except for the low frequency radars, the technology to deploy the other radar in space is quite mature. However, for the radar sensors several studies are required to determine the optimal configuration and processing algorithms. Specifically, for repeat passes with polarimetric interferometric radar we need to assess how much temporal decorrelation affects vegetation structure parameter extraction for a variety of biomes. For example, airborne measurements with a single pass L-band interferometer need to be compared with repeat pass observations for variety of time intervals and biomes. High frequency interferometric radars need to be studied for optimal incidence angle range and spatial resolution. Determining the optimal processing and multiple-baseline configuration for structure also needs to be assessed. For low frequency radars, the development of large spaceborne antennas and processing of data to deal with the effects of ionosphere on image formation and Faraday rotation for the polarimetric signatures.

3. Hyperspectral: The instrument technology and science applications of hyperspectral instruments have been demonstrated in the successful NMP EO-1 mission carrying Hyperion. There are no technology impediments to subsequent missions, but the desire for a wider swath width in order to reduce the revisit time (achievable through multiple satellites or creative focal plane design) was identified as a high priority. The potential of commercial competition has been cited as an obstacle but should be verified because it may no longer be a problem.

4. Multi-Angle Sensors: MISR on Terra has demonstrated the technology and application of multiple-angle optical sensors but its spatial resolution and other characteristics may need to be optimized for our applications. An aircraft demonstration, possibly using AIRMISR, leading to a spaceborne instrument is of great interest.

5. Synergy: The advantages of combining two or more of the instrument types above are particularly exciting. The complementarity of lasers and radars is important and has been discussed for some time; the prospect of combining hyperspectral or multi-angle optical sensors with lidar or radar is new and exciting possibility. The possibility of collecting aircraft data as part of an upcoming field campaign was discussed and endorsed.

6. Airborne Sensors and UAV Based Sensor: Airborne methods of demonstrating instruments, technology and the utility of data types and combinations of data types and of providing rapid response to disturbance events was discussed. UAV platforms were identified as possible candidates for future technology testbeds for sensor development and more continuous monitoring of regional areas for disturbance and its effects on the vegetation. Having multiple sensors on the same

platform for sensor fusion studies of vegetation was highly recommended

7. Other Desirable Attributes: Other desirable attributes include simultaneous high spatial resolution and high temporal frequency from space, calibration/validation, adequate ground and airborne validation, adequate pointing control and/or knowledge, possibly with active compensation, and miniaturized components.

Recommendations

- The highest priority lidar development is high repetition rates (> 300 shots/s) reliably sustained on orbit (5 year goal). Two color (red–NIR) laser development and lidar spot sizes as small as 10 to 25 m were identified as highly desirable for vegetation structure measurement. The group also recommended developing heterodyne quantum noise limited detectors for space based lidars, and multi-angle lidar with an angle separation greater than 20°. It was recommended that an airborne sensing prototype for a lidar sensor with these characteristics might be developed, possibly as part of an IIP demonstration.
- Radar technology is relatively mature and well-founded choices for air and spaceborne radars can now be made, however some additional tests are required: (a) For repeat passes with polarimetric interferometric radar assess how much temporal decorrelation affects vegetation structure parameter extraction for a variety of biomes. (b) Airborne measurements with a single pass interferometers need to be compared with repeat pass observations for variety of time intervals and biomes. (c) High frequency interferometric radars need to be studied for optimal incidence angle range and spatial resolution and the optimal processing and multiple-baseline configuration for structure. (d) For low frequency, radars develop large spaceborne antennas and methods to process data to deal with the effects of ionosphere on image formation and Faraday rotation for the polarimetric signatures.
- For hyperspectral sensors there are no technology impediments to subsequent missions, but the desire for a wider swath width in order to reduce the revisit time (achievable through multiple satellites or creative focal plane design) was identified as a high priority
- For multi-angle sensors, an aircraft demonstration, possibly using AIRMISR, leading to a spaceborne instrument optimized for vegetation structure.
- Develop sensor synergy/fusion, not just radar-lidar, but also with multi-angle and/or hyperspectral.
- Airborne or UAV testbeds are encouraged. Further, having multiple sensors on the same platform for sensor fusion studies of vegetation was highly recommended.

Techniques-Based Intercomparisons

Chair: Kathleen Bergen, University of Michigan
Rapporteur: Richard Fernandes, Canada Centre for Remote Sensing
Recorder: Wayne Walker, University of Michigan

Discussion

The group considered four questions as follows:

1. How should alternative approaches to deriving structural information from remote sensing be implemented and evaluated?

This should be done via field campaigns using multiple airborne sensors across sites. Prior to this, it is very important to define what are the ground truth standards for given measurements and then compare with these. For example, remote sensing-derived carbon stocks/flows would be compared to FIA or timber company estimates. To evaluate process level measures that could be derived from remote sensing, these new parameter estimates should be propagated into process models and compared to ground measurements of processes (e.g., carbon flux from towers). For process data, there is a need to include radiative transfer model testing in addition to flux/productivity models. Biodiversity measures of interest to derive from remote sensing have been identified through the Tahoe conference and this workshop.

2. What sampling strategies are needed for techniques-based intercomparisons using remote sensing, field and modeling?

It is clear that there are a number of potential forest structure cells in the matrix for techniques-based intercomparisons. There are thee major biomes: boreal, temperate, tropical and there are forest structural type and disturbance gradients within each these. It will most probably be necessary to subsample the matrix. Further, the actual sites may need to be intensive sites with sufficient structural, flux and process related measurements to evaluate both radiative transfer and process models. Ideally, sites would have existing measurement program and model studies, although there should also be opportunities to grow smaller or new sites where warranted and to collect very specific data. Another potential approach is to establish a network of regional sites corresponding to ~1 ha plots with some structural measurements. Stratify with Landsat or existing FIA data and then use aggregated (e.g., county level) FIA data sets to validate regional estimates.

3. What sensors should be evaluated?

Fine-and moderate-spatial resolution sensors are of the greatest interest to deriving forest structure information. Different scales are of interest to study the possibilities of scaling between ground, fine-resolution, and moderate-resolution remote sensing data, given that scaling is also of interest to land management agencies and organizations to increase efficiency and information content of sampling and measurement schemes. In addition to new sensors developed for forest structure measurement, current sensors would include (1) lidar (LVIS); (2) radar (AIRSAR/GeoSAR; ERS/PALSAR; Radarsat); (3) hyperspectral (AVIRIS, AirMISR, Hyperion), (4) fine and moderate-resolution optical, and multi-angle (MASTER, Landsat, EO-1, PALS, POLDER, CARABAS). Combinations of sensors of the different types should be evaluated together over the same sites to control for site differences in evaluating sensor capabilities and to evaluate potential added information gain from multi-sensor measurements or sensor fusion.

4. What should be the role of data availability in the community?

The group suggested there is a need for a data management group to assemble to provide quality assurance and document the relevant data sets. Use of ground data at non-NASA sites may need to be negotiated *a priori*.

Recommendations

- Stress and agree with other groups who have recommended field campaigns with multiple sensors to be evaluated on the same sites and tested against both field and model data.
- Ideal is to optimize field data needs by using on-going measurements in existing field sites/networks (e.g., LTER sites, etc.), but with some useful range of structural variability (not necessarily the entire range, but e.g., extremes and middle) and disturbance. With regards to biomes, consider which structures or disturbances will yield most useful information in each biome, likely will not have the resources to test on all ranges in all biomes.
- Initially focus on a few representative sites and compare measurements from different sensors with field and modeled data.
- The most important metrics are height (height itself, but also height as a component of biomass and in canopy layering), biomass, and composition (forest type/species). Algorithm development needed.
- Make data available to the greater community in an organized way that also assures quality.

Mission Requirements

Chair: Robert Knox, NASA GSFC
Rapporteur: Hank Margolis, Université Laval
Recorder: Jeanne Anderson, University of New Hampshire

Discussion

The objective of this group was to suggest how to best test the technology to provide long-term public access to broad spatial scale data on forest structure for science and applications related to estimating carbon stocks, ecological process modeling, and conservation of biodiversity. The group addressed the following questions: (1) how can space missions, new airborne sensors, field studies, airborne programs, data from existing technologies, new theory, and data synthesis workshops help meet the science goals? (2) What requirements for structure remote sensing should new missions be designed to meet? (3) What remote sensing requirements are best met with other types of capabilities? (4) What methods are available to evaluate measurement approaches using a common set of science/applications requirements? (5) What investments might help NASA meet high-priority science and applications goals while also stimulating major advances in remote sensing technology?

1. How can space missions, new airborne sensors, field studies, airborne programs, data from existing technologies, new theory, and data synthesis workshops help meet the science goals?

There is a good sense of the general science requirements now. Developing the technology to measure forest structure is imperative and we need to enable the technology to do it. We must first go from a qualitative to a quantitative definition of measurement requirements—accuracies and frequencies. We must conduct sensitivity analyses to test the consequences of different accuracy requirements, e.g., what happens when you go from one to two meters accuracy in height? Absence of information on how forest structure changes over time and space (e.g., disturbance and recovery) is so great that even modest improvements will have dramatic results. The capability to get broad-scale lidar information is imperative. It is an important message to give to the program managers. This is something that this community needs. This is an opportunity to move toward a mission that gets us there. We need a process to develop precise mission requirements and define how the greater community will use forest structure information. Need to weed out less defensible ideas and objectives. Need to identify measurements and accuracies and then circulate to the community for comments. Next-best alternatives should be defined as well. This process should have a short time period (six months to a year).

a. Space missions: Space sensors provide global access and potentially global coverage. Systematic needs (frequency of coverage) have to be defined as well. There is agreement that global access to forest structure data is important and space sensors are the only way to accomplish this. At present it is a bit too early in the process to precisely define how space missions can help meet science goals, but it should be kept on the table even while airborne missions are underway.
b. Airborne programs and field studies: Lidar—providing general access to LVIS data is a key step because difficult problems often require multiple brains. More LVIS instruments/products should be provided to a wider community. A VCL-type sensor should be redesigned and launched within five years. Radar—may move from older platforms (DC-8) to UAVs in the next five years. Both lidar and radar could benefit from UAV because of their improved navigational capabilities and repeatability, but these are public safety issues, permits, and flight speed issues that need to be considered. Airborne systems need to try out different possibilities of what can be done from space—different footprints, swath widths, repeat cycles. Sensor fusion is of key importance—we should fly lidars, radars, hyper-spectral and multi-angle radiometers in a coordinated manner. Sensor fusion usually requires specific funding and top-level coordination. We should build an airborne (and eventually a spaceborne) ***observatory for forest structure*** around sensor fusion. Airborne systems can provide regional sampling and characterization but not necessarily global estimates. FIA plots are spread out and not amenable to efficient airborne sampling. Need to define what are the simultaneity requirements for getting radar and lidar composite coverage.
c. Existing assets: Height data are needed right away - ALOS PALSAR (L-band) (Japan) has some potential interferometric capability and might be used for providing height information. Modifications to the planned solid earth SAR satellite may be possible—but we must know our requirements before asking for changes. The community should consider LVIS as it currently exists and commercial lidar sensors.
d. Data synthesis and data continuity workshops: Both synthesis activities and workshops are considered to be key to data fusion efforts. Modelers can request certain standard data sets for the workshops and instrument teams must then produce them for use at the workshop. Workshops can provide impetus for new algorithm development. Product continuity implies a significant effort to cross-calibrate between missions to provide long-term data sets of height, biomass, etc.

2. What requirements for structure remote sensing should new missions be designed to meet?

Although it would be a huge advance in our understanding, one pass is not enough. The Earth is changing and so we need a monitoring capability for forest structure over time. Frequencies will depend on specific science questions and biomes—but phenology over the growing season could be useful for many science questions and applications. Long-term monitoring implies that many significant issues regarding calibration must be addressed. There are no calibration standards for structure that currently exist. For example, calibration with reference targets, of instrument components, instruments, specific ground segments, etc. should be considered. A long process of instrument development can be incompatible with calibration and can interfere with science applications. The applications community requires a fair degree of stability of the instrument. Finding funds for technology development can be easier than finding funds for applications of the technology.

3. What remote sensing requirements are best met with other types of capabilities?

The community will need abundant ancillary ground level data, that although it may not necessarily be ground-truth, it can be used to develop synergy—so we need to take advantage of existing field plots and studies. Complete forest harvest for biomass assessment following a lidar or radar mission has never been done. Planned forest structure manipulation experiments from other agencies can prove useful for tests. The biggest limitation for lidar biomass is the allometry used to go from height (and DBH) to estimated biomass. Belowground carbon—the elephant in the room should be addressed.

4. What methods are available to evaluate measurement approaches using a common set of science/applications requirements?

Observing System Simulation Experiments (OSSE) for remote sensing structure—do we need them? OSSE creates simulated observations and then uses them to measure improvements in models. They are common in the meteorological and oceanographic communities. Example—generate height data, and then test if a model can perform better, e.g., at flux sites. OSSE could occur at both continental and landscape scales for forest structure endeavors.

5. What investments might help NASA meet high-priority science and applications goals while also stimulating major advances in remote sensing technology?

We must develop specific high-level science requirements so that the engineers can develop instruments to specific standards. Need to develop airborne sensor fusion strategies, possibly on UAVs—(lidar, radars, hyper-spectral and multi-angle radiometers) in a coordinated manner. Conduct well-planned multi-sensor field campaigns that include different biomes, disturbances, and manipulations that leverage existing field data. Design and deploy more instruments and increase data availability. Do either a request for proposals for defining science requirements or form working groups for moving this mission forward. Conduct sensitivity analyses for different measurement accuracies.

Recommendations

- Ultimately space sensors are the only way to achieve global coverage and access to forest structure data.
- Airborne missions should emphasize sensor fusion and the coordinated overflights of lidars, radars, hyperspectral, and multi-angle radiometers.
- Build an airborne and eventually spaceborne observatory for forest structure around sensor fusion.
- Height data is needed right away—explore options for using ALOS/PALSAR, LVIS and commercial lidars.
- Earth is changing, so need monitoring capability for forest structure over time (over seasons and annual periods).
- Revisit a VCL-type sensor for launch within 5 years and explore UAV-based or other new radars and radar interferometers.

Synthesis: Appropriate Next Steps

Science

Discussion Leaders: Richard Houghton, Hank Shugart, and Kathleen Bergen

Biomass and Carbon science and management questions and data needs include those focused on: (1) ecology (e.g., regional-global distributions and change in vegetation biomass), (2) natural resources (e.g., timber management), and (3) carbon accounting (stocks and changes in stocks). While some data exists, we currently lack spatially explicit information on biomass/carbon stocks, and estimates of carbon stock dynamics or change for most areas of the world at useful spatial and temporal resolutions and at the desired accuracy/precision. In terms of specific measures, we need to know carbon densities (Mg C/ha) with high accuracy and precision plus rates or carbon sequestration or removal. While total carbon is important, component measures (height, crown cover, basal area and density) are important. Direct measures from remote sensing should be investigated, and at the same time, new types of allometric equations not based on DBH may need to be developed to be compatible with remote sensing data. Two measurement approaches—sampling and wall-to-wall—need to be co-evaluated. Both need to pay attention to precision of the measurements or estimates. In terms of spatial scale, finer resolution will probably be needed for timber management and ecology than required for carbon accounting—both are important.

Process Studies are concerned with canopy-level, stand, and landscape processes. The spatial and temporal scales of forest structural data needed for the first two in particular are relatively fine-scale. For canopy-level processes, need fine scale LAI and LAI profile data (< 3 days and 1–3 m horizontal-vertical spatial resolution). At stand and landscape levels, need to map disturbances plus canopy cover/LAI with 3–5 m resolution (stand) and < 30 m resolution (landscape). For the range of process studies, relevant remote sensing products include tree heights and stem clumping (gaps), leaf area and type, and canopy vertical distribution, angles and clumping, woody biomass, stem size, number of stems, canopy nitrogen concentration, and physical environment measures that serve as common inputs to process models. Formal tests of sensor capabilities, scale dependencies, and accuracies/precision are needed. New or revised models plus visualization capabilities that capture the multi-dimensional structure and processes are very important the feasibility of using remote sensing derived forest structural data in studies of ecosystem processes.

Biodiversity science and management is concerned with both vegetation and animal diversity. Information needs are at the scales of species, communities and ecosystems. Critical issues revolved around the fact that landscapes worldwide are rapidly changing in terms of forest composition and structure, including extinctions and invasive species, and real strategic decisions are being made as to what biodiversity should or will be maintained on the landscape. At the species habitat level, inputs to management level habitat models currently are limited to field data for structure information. At the landscape level, if the model concerns a larger region, there is little inclusion of structure. In terms of desired structural attributes to meet science needs they include: (1) what: composition—need improvement in accuracy (from ~80 to > 90%); (2) physiognomic diversity: e.g., conifer overstory, deciduous understory, etc; how distributed: canopy cover, vertical diversity (e.g., canopy layers, foliage height diversity); (3) how much: biomass, productivity, crown volume; (4) change: phenology, disturbance. To achieve these needs for biodiversity information, overall approaches may include: fusion of sensor capabilities will be advantageous to retrieve these desired parameters—lidar, radar, and hyperspectral. There is also a need to develop a new generation of models that incorporate multi-dimensional structure and at different resolutions.

Remote Sensing

Discussion Leader: Sassan Saatchi, NASA JPL

As the remote sensing section of this workshop report has shown, several remote sensing techniques have strong potential to provide greater information on the three-dimensional structure of forests. Lidar has strengths in resolving height and vertical profiles and with relatively fine vertical resolution. Radar has strengths in direct estimates of forest volume, biomass, and carbon; has potential vertical profile capabilities; and is an imaging (spatially continuous vs. transects) all-weather active sensor. Multi-angle sensors can provide unique information related to gaps and light interception. Hyperspectral sensors have strengths in deriving parameters related to water, chlorophyll and other chemical constituents, and dry matter. Data fusion of radar/lidar or other sensors with radar or lidar could augment capabilities. Technical questions that cut across sensors relate to sampling vs. mapping and scaling.

Currently there are varying degrees of technological maturity and maturity of the algorithms necessary to process the data to provide the most accurate information possible. We need to eventually move from measurements to products useful for scientific and other communities. Algorithms need to be developed and refined that are directly intended to derive landscape and forest structure and composition. The robustness of these algorithms in different environmental conditions and different measurement configurations as well as scaling issues needs attention and analysis.

To best propel the technology and algorithms for the several key sensors forward, an intercomparisons approach is needed. There needs to be comparison with field data and good validation. The complementarities of sensors should be stressed, and this should lead to sensor/data fusion. Sampling vs. mapping needs to be analyzed. Community development should be stressed—we need to think beyond just single sensors or techniques.

Ultimately there should be a transition to spaceborne systems. To do this we need to define science goals, the measurement approaches, and data products. We need to define the specific technology requirements, development strategies, pathways and timelines. We should simultaneously define processing, archiving, and data/products distribution. The use of existing assets for the transition process is encouraged.

Programs

Discussion Leader: Robert Knox, NASA GSFC

Workshop sessions affirmed the need for measurements of forested ecosystem structure, using methods that provide global access and/or global sampling (depending on the application or science question). Participants also took exception to the suggestion that providing such measurements should wait until requirements are more mature. An initial set of globally consistent structure measurements would enable major qualitative advances in several key areas. Nonetheless, coordinated field programs and work to analyze and refine requirements are needed. There also was a consensus to form a working group to sustain community participation in taking the next steps. Critical areas of community involvement include: helping develop the recommended field programs, analysis and review of requirements for remote sensing observations, staying engaged with technology development for remote sensing of structure, and data fusion. Plenary discussions emphasized that this working group should aim to be international in scope and take steps to encourage participants from developing countries.

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14. ABSTRACT

This workshop brought together two science communities—ecologists and remote sensing technologists—to help define NASA requirements for remote observations of multi-dimensional forested ecosystem structure. The workshop was designed to: clarify the key scientific goals of and requirements for remote measurements of forested ecosystem structure, identify the most relevant remote sensing technologies and their capabilities, and recommend methods by which NASA can evaluate measurement approaches using a common set of requirements. The format consisted of plenary presentations followed by breakout sessions on science (carbon/biomass, process studies, biodiversity), technology (remote sensing, models), and planning. This document summarizes the outcomes of the workshop.

15. SUBJECT TERMS

Ecology; remote sensing technology; forested ecosystem structure; carbon/biomass; process studies; biodiversity; remote sensing models.

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