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Introduction to special section on Remote Characterization of Vegetation Structure: New Methods and Applications to Landscape-Regional-Global Scale Processes

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[1] This special section stems from three sessions focusing on the "Remote Characterization of Vegetation Structure" that were held at the fall meeting of the American Geophysical Union (AGU) in December 2006, San Francisco. The sessions were well attended with more than 40 abstracts covering a range of poster and oral presentations. High levels of interest in this topic have led to the establishment of a de facto regular session within Biogeosciences at the fall meeting, with a similar number of abstracts presented in 2007 and a session planned for December 2008. The goal of these sessions was to highlight how recent advances in active and passive remote sensing technology, data acquisition methods, and analytical techniques could be used to both characterize vegetation structural metrics at multiple scales, and to further understand how these measures could be used as inputs in biogeochemical, biophysical, and ecological models. The papers in this special section represent the highlights of the latter objective and include participants from the conference special sessions, along with scientists from the wider scientific community. A companion special issue focusing on the former objective has been organized in the *Canadian Journal of Remote Sensing* and is due to be published in the fall of 2008. In this introduction, we provide context for this special section, summarize the main results of each contribution, and include suggestions for further strategic directions and activities in this area of research.

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1. Introduction

[2] Recent advances in remote sensing technology, methodology, and analytical approaches have opened up numerous opportunities to characterize vegetation structural attributes such as height, crown shape, crown architecture, and canopy shadowing from the individual plant to regional scales. For example, the recent application of aerial and satellite based laser altimetry systems (i.e., light detection and ranging, "LiDAR") has enabled the remote characterization of three dimensional forest canopy structure information. A further notable advance has been the increase in studies employing object-orientated data analysis algorithms [e.g., *Chubey et al.*, 2006; *Falkowski et al.*, 2006]; where rather than using methods that analyze each pixel independently, this new generation of methods is able to identify clusters of similar pixels or points as image objects. Subsequent analysis can then produce measurements relevant to each individual object, such as its size, or growth if multitemporal imagery is applied.

[3] In forestry research, such remote sensing data and analysis methods have been used to determine canopy architecture with increasingly higher precision. Although studies have sought to use these measurements to further the prediction of biomass and carbon via allometric relationships [*Strand et al.*, 2008], a next step forward is to directly relate and input these spatially explicit measurements of canopy structure, such as size and distribution of canopy gaps, and other landscape features (e.g., snowdrifts, landforms) into landscape-scale process models that include and/or predict budgets of water, biogeochemistry, and energy. Continuing to extend these efforts beyond forested ecosystems by characterizing additional landcover types such as savannah, shrub-steppe, grasslands, and wetlands will likely enable the development of new inputs to landscape-regional-global scale biogeochemical process models and improved understanding of feedbacks among vegetation characteristics, biogeochemical pools/fluxes, and climate. Indeed, the new understanding of vegetation structure gained from remote sensing data of high spatial resolution yet broad spatial extent could potentially be used to evaluate vegetation functional group classification, vegetation successional

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dynamics, and light/water interception, among other topics. This special section presents a collection of papers that highlight several complimentary themes relating to the spatial and temporal aspects of some of these challenges.

2. Mining the Riches of Multitemporal Data

[4] The temporal extent of vegetation structure assessments can be broadened through increased application of aerial photography, which has been collected since the late 19th century. *Strand et al.* [2008] highlighted the quantitative potential of such data by employing a multiscale object-orientated method to measure the location and canopy width of each western juniper within imagery obtained in both 1939 and 1998. Using this approach across multiple spatial scales, *Strand et al.* [2008] determined the 60 year change in aboveground woody carbon stocks for a 330,000 ha region of North America resulting from juniper encroachment.

[5] *Helmer et al.* [2008] combined remote sensing imagery from 1991 to 2000 with forest inventory data to evaluate patterns in forest age and the impacts on carbon storage and tree species richness in Puerto Rico. Among other findings, this study reported that not accounting for the forest age results in nearly a 20% underestimate in the biomass removed via land development [*Helmer et al.*, 2008].

[6] These two studies underscore the value of temporally deep remote sensing data records to understand decadal scale vegetation shifts that can accompany land use and land cover change. While such multitemporal comparison studies are at present largely limited to passive remote sensing data sets, similar multitemporal investigations will become increasingly possible with active LiDAR and RADAR data over time. Therefore, as the scientific community continues to realize and articulate the importance of preserving data continuity with sensors such as AVHRR, MODIS, and Landsat, it is similarly vital to acquire LiDAR and RADAR data sets across broad extents and varied biomes to serve as benchmarks for future comparison.

3. Widening the Geographical Extent

[7] Broadening the coverage of active remote sensing data sets is necessary to enable remote characterization of fine scale vegetation structure in the myriad biomes occurring across the globe. For example, the majority of vegetation studies using airborne LiDAR have focused on forested ecosystems [*Nelson et al.*, 1988; *Dubayah and Drake*, 2000; *Means et al.*, 2000; *Falkowski et al.*, 2006], with fewer studies focused on quantifying low-lying vegetation associated with rangelands [*Streutker and Glenn*, 2006] or riparian systems. As these applications expand, it will be important to cross-validate methods for deriving ground and canopy surface morphologies using LiDAR across a range of vegetation functional types and biomass conditions [e.g., *Ritchie*, 1996; *Dubayah and Drake*, 2000; *French*, 2003; *Evans and Hudak*, 2007]. For example, *Antonararkis et al.* [2008] highlight the importance of deriving accurate measures of LiDAR derived vegetation roughness to identify individual trees and to characterize hydraulic resistance of vegetation occurring along a riparian corridor. *Antonararkis et al.* [2008] conclude that accurate delineation of individual crown width in their dense deciduous riparian forest canopy was the limiting factor in determining stem roughness, a key parameter in deriving canopy hydraulic resistance.

[8] Increased use and application of low Earth orbit and satellite-based LiDAR and RADAR sensors in addition to Quickbird and IKONOS that can obtain globally extensive data is a natural next step to extend the geographical extent of vegetation structural assessment. Examples of such sensor platforms include the Geoscience Laser Altimeter System (GLAS), which was launched aboard NASA's Ice, Cloud, and land Elevation Satellite (ICESat) in 2003; RADARSAT; and the Shuttle Radar Topography Mission (SRTM) data that was flown on the Space Shuttle Endeavor from 11 to 22 February 2000.

[9] Accurate assessments of vegetation structure from the GLAS sensor require that the sources of error and uncertainty be thoroughly evaluated. In the work of *Neuenschwander et al.* [2008] the dependence of the waveform shape on vegetation structure and topography were evaluated and compared to airborne LiDAR data in a sparsely vegetated desert calibration site and a shrub woodland ecosystem. Their study found that under leaf-off conditions the two data sets corresponded well but over vegetated areas the GLAS-derived digital ground elevations exhibited a 1-m bias [*Neuenschwander et al.*, 2008]. This result is important for GLAS-based assessments of biomass for the global carbon budget, given that vegetation heights rely on the surface elevation, and further highlights the need to conduct similar evaluations of surface model bias within other data sets, including airborne LiDAR.

[10] *Ribeiro et al.* [2008] explored the utility of RADARSAT data to infer woody biomass and LAI for the Niassa Reserve in Mozambique, Africa. Their results demonstrated that RADARSAT enabled reasonable predictions of both woody biomass ($r^2 = 0.55$) and LAI ($r^2 = 0.45$). Also in Mozambique, *Fatoyinbo et al.* [2008] evaluated the ability of SRTM data to infer landscape-scale vegetation height, biomass, and carbon pools and produced an estimate of 11.8 million tons of carbon as being present within that country's mangrove forests.

4. Into the Future

[11] Technological advances will undoubtedly continue to further extend the scientific community's ability to quantify vegetation structure at increasingly higher spatial resolutions and broader spatial extents. While achieving the highest level of spatial resolution and extent will continue to be mutually exclusive using any one sensor, the capability to calibrate satellite-based data using high resolution passive and active remote sensing data sets acquired at various points around the globe will enable further assessment of errors and uncertainties inherent in regional- to global data sets and model products. In addition, our increased ability to gather and analyze remote sensing data to derive vegetation structure across a range of scales from 10^{-3}m spatial sampling [*Clawges et al.*, 2007] to global extents [*Lefsky et al.*, 2005] may enable hierarchical analyses to test and inform scale-independent relationships between vegetation structure and function [e.g., *West et al.*, 1997]. It is however apparent that as technology proceeds and more data comes available from airborne and satellite systems that a network of ground validation sites should be established that cover a

range of vegetation structure (i.e., from boreal and mixed conifer forests to sage-steppe and riparian zones) and surface morphology. These sites could include both well documented ground and vegetation inventory surveys in addition to airborne LiDAR data collected under accepted and consistent standards. Establishment of this network would provide rapid determination of the bias and uncertainties in any proposed vegetation structure and surface morphology product; allowing error propagation assessments to further constrain the uncertainty in regional-global water, biogeochemistry, and energy budget estimates.

[12] A number of specific initiatives are currently under development that would help establish widespread and comprehensive baseline data against which future measures of vegetation structure can be compared. For example, the USGS is currently leading a planning effort to acquire a high resolution, high accuracy LiDAR data set for the entire United States [*Stoker et al.*, 2007], while NASA is in the process of refining a mission concept for the DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice), a two-sensor satellite platform that would gather simultaneous data from an interferometric synthetic aperture radar and multiple beam LiDAR [*National Research Council* (*NRC*), 2007]. These two planning efforts mark an exciting time where the scientific community can begin plans to link ground-based biogeophysical data collected from existing networks of experimental watersheds and ecological research sites, with spatially extensive and temporally frequent vegetation structure data. This future marriage of ground based process data with remotely detected structure data holds great promise indeed to serve as the foundation for the next generation of biogeophysical process models linking ecosystem structure and function. Such advances may potentially lead to "remote sensing aware allometry," where carbon and biomass are derived via remotely sensed tree parameters such as height, crown area, 3-D crown shape, etc., instead of the traditional field focus on diameter at breast height.

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