Moving Toward Consistent ALS Monitoring of Forest Attributes across Canada: A Consortium Approach

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Abstract

As airborne laser scanning (ALS) gains wider adoption to support forest operations in Canada, the consistency and quality of derivative products that support long-term monitoring and planning are becoming a key issues for managers. The Canadian Consortium for Lidar Environmental Applications Research (C-CLEAR) has supported almost 200 projects across Canada since 2000, with forest-related studies being a dominant theme. In 2010 and 2011, field operations were mobilized to support 13 ALS projects spanning almost the full longitudinal gradient of Canada's forests. This paper presents case studies for seven plus an overview of some best practices and data processing workflow tools that have resulted from these consortium activities. Although the projects and research teams are spread across Canada, the coordination and decade of experience provided through C-CLEAR have brought common methodological elements to all. It is clear that operational, analytical and reporting guidelines that adhere to community accepted standards are required if the benefits promised by ALS forestry are to be realized. A national Lidar Institute that builds upon the C-CLEAR model and focuses on developing standards, guidelines, and certified training would address this need.

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Introduction

Since the mid-1990s, airborne laser scanning (ALS) has been increasingly adopted to support the study of vegetation canopy structure and the management of forest resources (Lim *et al.*, 2003; Hudak *et al.* 2009). Today, government and industry land resource stewards operationally collect and analyze ALS data to support a range of management needs (Næsset *et al.*, 2004; Evans *et al.*, 2009; Woods *et al.*, 2011). Meanwhile, researchers frequently obtain raw ALS data and derivatives to support ecosystem classifications (Johansen *et al.*, 2007) and modeling (Lefsky *et al.*, 2002). In Canada, a country with vast and remote forest cover of high economic and environmental value (Wulder *et al.*, 2008b), the potential benefits of ALS for forest research, management, monitoring, and planning are great. Despite widespread use of ALS for forest characterization, there remains limited standardization of data acquisition, processing, and analysis (Reutebuch *et al.*, 2005; Wulder *et al.*, 2008a; Evans *et al.*, 2009). For example, variations in ALS data collection procedures can result in differences in derived canopy attribute information (Chasmer *et al.*, 2006; Hopkinson, 2007; Næsset, 2009). This lack of standardization means stakeholders often develop their own procedural solutions or are forced to adopt suboptimal procedures designed to meet needs different than their own. This can limit the adoption of ALS in situations where it is ideally suited and therefore reduce the breadth and depth of realizable benefits to forest managers and researchers. Given the variety of forest cover types across Canada (up to 180 tree species, spanning nine ecozones), the differing levels of private, municipal, provincial, and federal stewardship and range of industry sector interests, the challenge of standardization is acute.

Minimal standardization is expected given rapidly evolving technology and software, combined with a variable and changing appreciation of the applications to which ALS data are suited. Further barriers to standardization are that many ALS studies have been conducted in areas of limited geographic variability, by a range of data providers adopting multiple systems and configurations, and for end users across many sectors and jurisdictions. Under such a scenario, it is challenging to develop consensus, as no single stakeholder

Photogrammetric Engineering & Remote Sensing
Vol. 79, No. 2, February 2013, pp. 159–173.

0099-1112/13/7902–159/$3.00/0

fully appreciates the range of capabilities or needs of the entire community. Yet, community-endorsed standards are needed to develop consistent acquisition, processing and modeling protocols, data and reporting formats, training accreditation, and certification, and so that associated decision support workflows can be more widely understood and implemented. Without standardization, the comparison of inter- and intra-jurisdictional project data and results can be time consuming or even misleading.

Currently, society-hosted volunteer stakeholder groups like the "Lidar Division" (formerly the Lidar subcommittee) of the American Society for Photogrammetry and Remote Sensing (ASPRS) work to build consensus and support for the standardization of lidar industry practices (*http://www.asprs.org/Standards/*). The US Geological Survey is also developing generic ALS project specification guidelines (Heidemann, 2011). Within the international forest community, pertinent advances in ALS technology, practices, and research are disseminated at conferences: notably the SilviLaser series of annual meetings (since 2002). In Canada, there is an active community of researchers and practitioners addressing forest community needs for optimal ALS-based decision-support workflows, but due to geographic constraints, integration of these efforts at a national or even provincial scale is limited.

Since 2000, the Canadian Consortium for Lidar Environmental Research (C-CLEAR) has provided Canadian forestry communities with coordinated and consistent nationwide ALS data acquisition research support. C-CLEAR was initiated at Optech, Incorporated (Toronto, Ontario, Canada) as a cost-effective means of developing new applications for ALS by government and academic researchers. From 2004 to 2011, C-CLEAR gained direct access to Optech, Inc. ALTM 3100C and ILRIS3D sensors through a partnership with the Applied Geomatics Research Group (AGRG) at the Nova Scotia Community College (Hopkinson and Maher, 2009).

C-CLEAR has supported projects in Canada, USA, South America, Australia, and Europe that ranged in scope from Arctic coastal mapping (Whalen *et al.*, 2009) to Andean glacier inventory (Huh *et al.*, 2012) to error propagation modeling (Goulden and Hopkinson, 2010). Forest-related research was the dominant theme accounting for almost 50 percent (Table 1) of the almost 200 projects supported. Within the international ALS stakeholder community, however, forestry was ranked seventh with only 38 percent of ALS users in all sectors considering this an important application (Carey and Associates, 2009). This apparent disparity in priorities between research emphasis and stakeholder operational interest could be because standardization of ALS procedures in the forestry sector is still in its infancy.

The initial goal of C-CLEAR was to develop new applications for ALS data, however, other benefits were soon realized, including knowledge transfer, support for project design and the development of operational procedures. C-CLEAR "outreach" campaigns made ALS accessible to potential end users (as costs were subsidized), resulting in further applications development within marginal lidar markets. In recent years, the acquisition of repeat datasets over research sites in Canada has enabled the investigation of monitoring strategies (Hopkinson *et al.*, 2008) and survey configuration sensitivities (Chasmer *et al.*, 2006; Hopkinson, 2007; Lim *et al.*, 2008). ALS-based forest monitoring and survey design are popular research themes, as they deal directly with operational concerns related to data consistency, accuracy, and the ability to catalog growth and disturbance. Through C-CLEAR, such questions have been addressed by comparing: (a) inter- and intra-annual data variations over the same site, (b) datasets collected using equivalent parameters but over regional and national gradients, and (c) spatio-temporally coincident datasets collected using variable survey configurations.

Objectives

This paper describes the aims and outcomes of some recent projects supported by C-CLEAR. The case studies address a range of problems in forested landscapes related to resources assessment, monitoring, modeling, and operational workflows. Based on lessons learned from the case studies, some best practices are discussed, spanning the acquisition, processing, and derivation of forest-related products across several application domains. Given the range of applications and geographic extent represented, it is evident that a centrally coordinated "consortium" approach to nation-wide ALS research support has enhanced opportunities for the development of consistent and efficient procedures, while providing a foundation for standards development. The paper discusses some areas of best practice development related to the studies presented, and concludes with a brief proposal for a Lidar Institute dedicated to developing nationally relevant standards for ALS-related procedures.

Trans-Canada Case Studies

The projects supported by C-CLEAR (and AGRG) during 2000 to 2011 have resulted in a substantial ALS knowledge base (Table 1). Recent projects were selected to illustrate efforts toward the development of best practices around acquisition, processing, and analysis in support of ALS monitoring of forest attributes. During the summers of 2010 and 2011, greater than 30,000 line km of ALS polygons and transects were captured over eight of nine major forested ecozones in Canada, from the Atlantic coast to the western sub-Arctic (Figure 1). One project, in partnership with the Canadian Forest Service (CFS), was national in scope and involved flying transects across the country to support a range of research questions and satellite image calibration needs (Hopkinson *et al.*, 2011b; Wulder *et al.*, 2012). All other projects had region-specific objectives, many involving repeat surveys: Nova Scotia (biomass energy); Newfoundland (wood fiber quality); Quebec (point cloud simulation and biomass modeling); Ontario (growth monitoring); central Saskatchewan (carbon assessment); northern Alberta (hydrology, ecology and disturbance); the Northwest Territories (satellite-based forest inventory). These projects (locations illustrated in Figure 1) are summarized below from east to west.

Newfoundland Fiber Inventory

The enhanced fiber inventory project in Newfoundland was born out of a need to reduce costs, increase profitability, and position the forest sector for long-term economic sustainability. Specifically, the industry currently contends with operational inefficiencies due to uncertainty in: (a) the location and quantity of raw materials within inventory databases, and (b) optimal allocation and use of those raw materials in the most cost-effective and profitable manner (Mackenzie and Bruemmer, 2009). Enhanced inventory data are expected to help ensure the future of the one remaining pulp and paper mill in the province (i.e., Corner Brook Pulp and Paper Limited), while also helping the forest sector take advantage of new opportunities in bio-energy, bio-chemical, and biomaterial products.

ALS data were acquired during the peak growth in 2010 and 2011 for polygons and transects covering ~1,193 km^2 of

Table 1. Sample of Research Productivity Resulting from C-CLEAR Supported Projects from 2002 to 2011. (Based on Feedback from Partners and an Internet Search; Results Incomplete)

Institutions supported (incomplete list)	No. of peer-reviewed publications/books		No. of conference presentations		No. grad student /post-doc support	
	Forest	All other	Forest	All other	Forest	All other
Universities/Colleges						
Acadia University	5	3			2	5
Applied Geomatics Res. Group, NSCC	7	8	13	17	1	
Carleton University		2				
Dalhousie University		3				2
Queen's University	15	3	20	3	3	
Simon Fraser University				1		
Trent University						1
U. of Alberta		3				1
U. of British Columbia	2	2	1			
U. of Calgary		5		5		
U. of New Brunswick		2				2
U. of Northern British Columbia		1				
U. of Ottawa		1				1
U. of Quebec at Montreal	3		1		2	
U. of Quebec at Ottawa	2		2		1	
U. of Saskatchewan		9		5	4	
U. of Toronto		4				2
U. of Waterloo				1		
U. of Western Ontario	3	2			1	1
Wilfrid Laurier University	5	6	14	8	4	2
Government						
Agriculture Canada						
- Moncton, NB		1		1		
Environment Canada						
- Saskatoon, SK		6		3		
Geological Survey of Canada						
- Ottawa, ON		1		1		
- Dartmouth, NS		2				
Canadian Forest Service						
- Victoria, BC	1		1			
- Edmonton, AB					2	
- Corner Brook, NL						
Yukon Geological Survey		2		2		
Emergency Measures Organization, NB						
International Institutions						
Ohio State U. – USA		1				1
U. of New Hampshire – USA				1		1
Bournemouth U. – UK	2		2			
U. Nottingham – UK	1					
U. Reading – UK				3		
Swansea U. – UK	3		4		1	
CSIRO – Australia	3		2			
Total	**51**	**66**	**61**	**50**	**20**	**19**

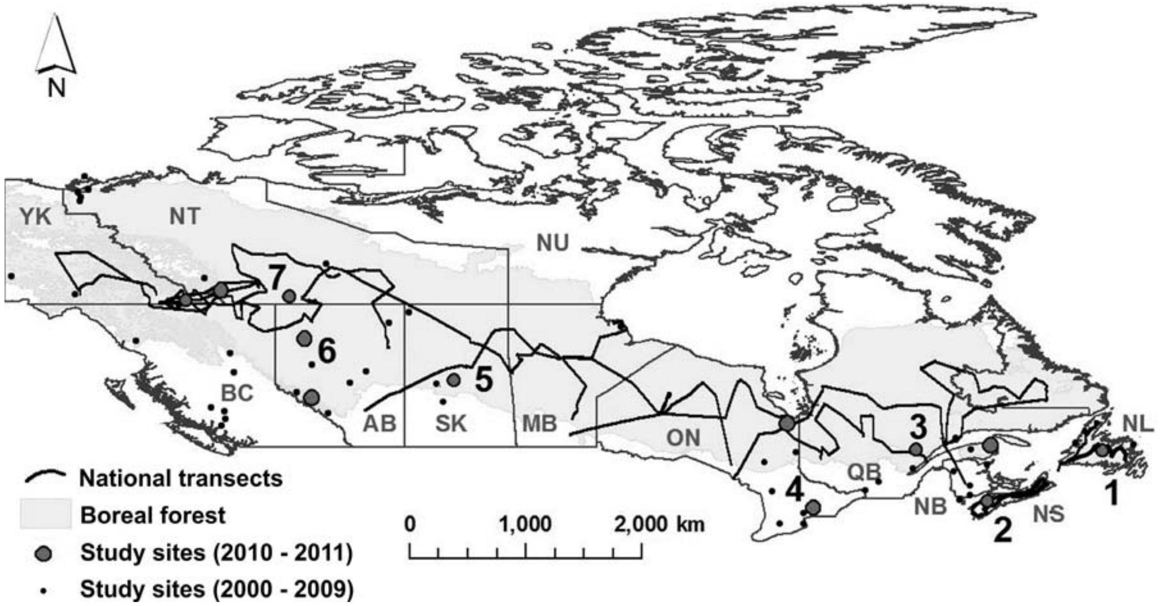

Figure 1. C-CLEAR supported missions across Canada during the summers of 2010 and 2011 illustrating CFS national sampling transects and individual study sites. Numbers refer to projects discussed below.

the commercial forest area in Newfoundland. The ALS data coincide with 72 field plots selected from a network of permanent sample plots (PSPs) maintained by the provincial forest service and representative of the range of species, height, crown density and site index classes (Figure 2). These data were supplemented with terrestrial laser scanning (TLS) data of fiber-cored trees from which fine-scale structural information can be derived and linked to ALS-derived data products (Côté *et al.*, 2010). The database is being used to develop ALS-based models of key forest attributes (e.g., Woods *et al.*, 2009 and 2011) which are used to support ALS sampling for a large-scale inventory across Newfoundland's commercial forest landscape. Accurate and consistent ALS metrics are imperative for modeling and predicting fiber quality attributes over such a large land base. Moreover, comparisons between ALS surveys over different years and across the region (Figure 2) are informing best practices and standardization within and between datasets for optimal wood fiber quality assessment.

Nova Scotia Biomass Inventory

The Province of Nova Scotia has committed to 25 percent renewable energy supply by 2015 and 40 percent by 2020, and forest biomass was suggested as a potential source of long-term carbon-neutral alternative energy to supplement more traditional sources (Nova Scotia Department of Energy (NSDE), 2010). Furthermore, revenues in Atlantic Canada from sawlog and pulp wood forestry products, critically important to the rural economy, have been in steady decline (Atlantic Provinces Economic Council (APEC), 2008). As a first step in addressing these energy and socio-economic needs, a province-wide spatially explicit forest biomass inventory was needed. Coarse estimates of forest biomass were previously derived by applying allometric biomass equations (Lambert *et al.*, 2005) to provincial PSP data and aggregating at the ecoregion level (Townsend, 2008). However, scaling from PSPs to forest resource inventory (FRI) stand polygons is limited by within-stand heterogeneity.

ALS data were used to model biomass directly and then to train a stand-level model that could be applied to the entire province. Approximately 20 percent (or 10,000 km^2) of Nova Scotia was previously mapped by the AGRG but to ensure all ecoregions were represented, strategically positioned transects were flown over representative PSPs around the province (Figure 3). PSP biomass estimates (Lambert *et al.*, 2005) were used to train ALS models using height percentile and return ratio metrics, and a stand-level biomass model was constructed using mean stand height and canopy cover metrics from the FRI database. This approach yielded a whole tree dry biomass estimate for Nova Scotia of 373 × 10^6 tons ±39 percent (Hopkinson *et al.*, 2011a). Integrating PSP, FRI polygon and ALS data collected over several years and using different survey configurations poses an operational challenge for many large-scale inventory projects. Some insights and potential solutions to this type of problem will be discussed later.

Quebec Forest Resource Inventory

Multiple ALS survey polygons were flown in Quebec (Figure 1) to support research into FRI attribute modeling, silvicultural practices, and ALS survey planning optimization. All acquisitions were planned at high point density (5 to 8 pts/m^2), as the over-arching objective was to develop and operationalize methods for individual tree crown and gap detection, as well as to obtain area-based estimates of FRI parameters such as height, diameter at breast height, crown length, and diameter. With the improved description of forest structure afforded by high point densities, optimization procedures for selective harvesting operations are being developed, with the goal of creating more complex forest structures with richer biodiversity. The surveys covered a range of forest types, from temperate mixed woods to boreal black spruce (*Picea mariana*) stands, and from young managed stands to old-growth natural forests.

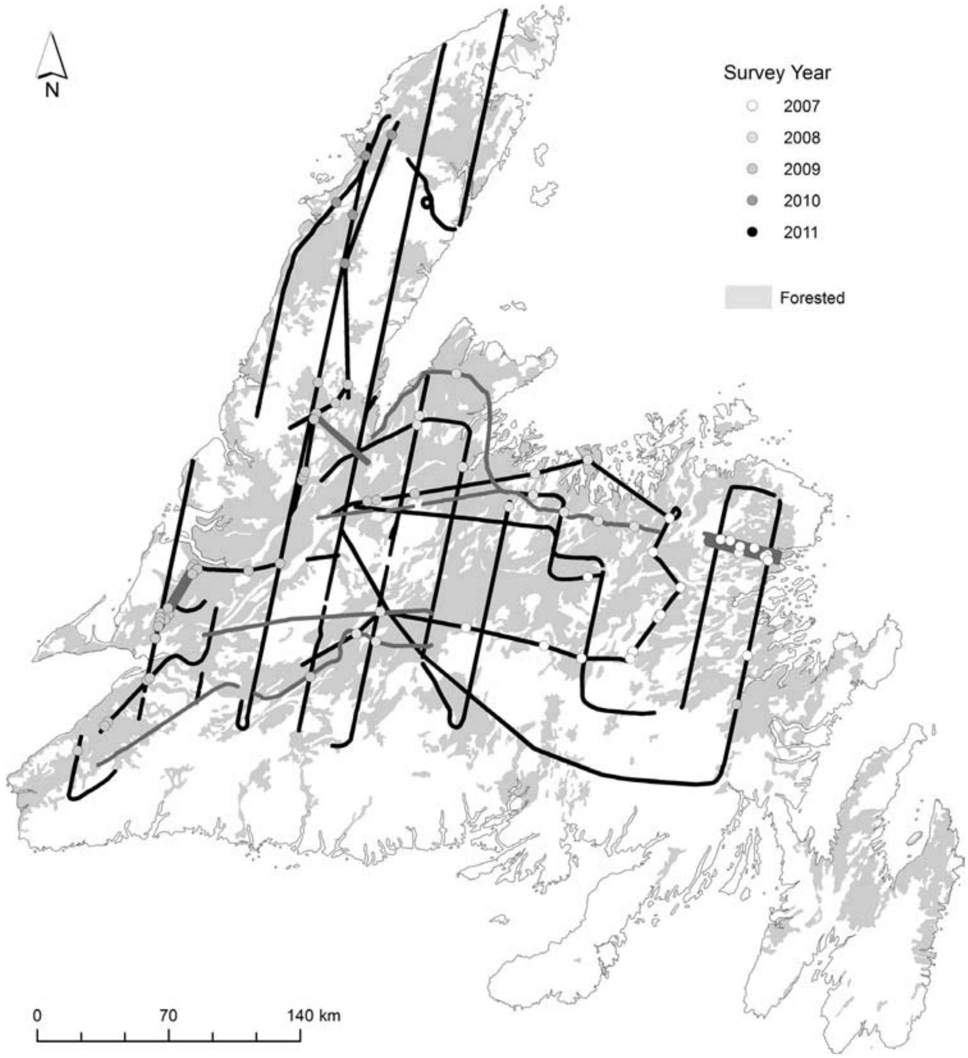

Figure 2. ALS survey polygons and transects with spatially coincident PSPs for the island of Newfoundland.

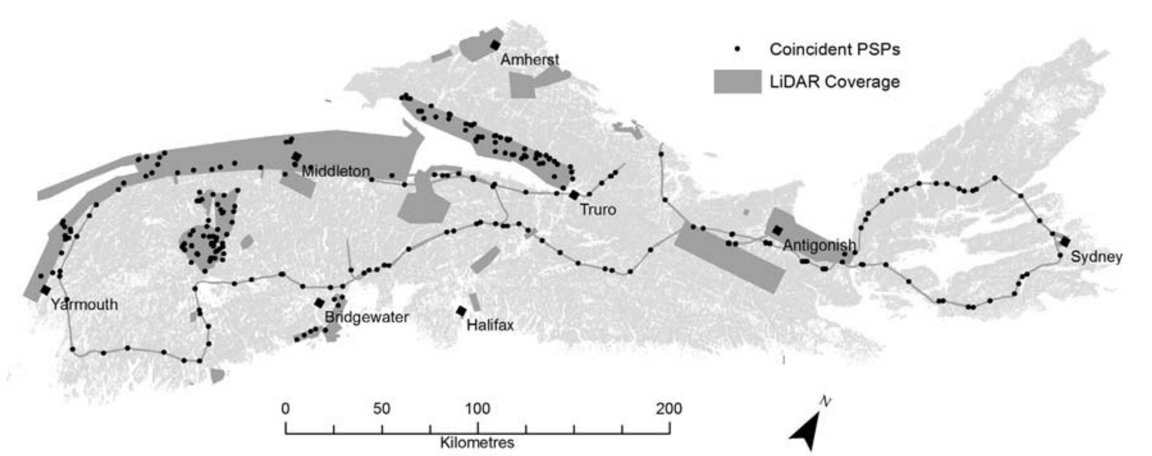

Figure 3. ALS data coverage available for biomass training and PSPs used in biomass model training that are within two years of spatially coincident ALS data.

Similar to the Newfoundland project, TLS data were acquired concomitantly with field and ALS data to research methods for extracting fiber quality attributes from point clouds. Quality indicators (such as stem taper or size of the largest branch) are extracted from the TLS point cloud to create a field reference. ALS metrics are then calculated and linked to this reference. The development of models and procedures to link plot-level TLS and wide-area ALS sampling will ultimately help managers better understand wood quality levels across their holdings before harvesting and thus extract higher value from the forest.

Ontario Growth Monitoring

In 2000, the Vivian Forest research site, 50 km north of Toronto (Figure 1), was selected for long-term ALS sampling as it displayed a range of managed plantation and natural forest stand types, and it was adjacent to Optech, Incorporated's ALS testing and calibration area. Since 2000, 12 datasets have been collected that range in quality, configuration, and time of year. Consequently, this site has supported several projects requiring repeat data acquisition: e.g., snowpack depth mapping beneath forest canopy (Hopkinson *et al.*, 2004); the influence of laser power and pulse repetition frequency (PRF) (Chasmer *et al.*, 2006) and sampling point density (Lim *et al.*, 2008) on derived canopy attributes; and repeat interval requirements for ALS-based forest growth monitoring (Hopkinson *et al.*, 2008). The site was surveyed again in 2011 using acquisition settings comparable to previous data collections to evaluate optimal repeat time intervals for slower growing and more heterogeneous forest stands. This research is providing guidance on the operationalization of ALS-based forest growth and disturbance monitoring strategies.

Saskatchewan Forest Carbon Monitoring

Approximately 30 percent of CO_2 emissions from fossil fuels are sequestered by terrestrial ecosystems each year (Canadian Carbon Program (CCP), 2011). Two approaches for estimating the C balance of forests are eddy covariance (EC) (Baldochi, 2003) and biomass inventories (Landsberg and Waring, 2004). The development of new approaches linking EC, plot data, ALS and satellite products (e.g., Chasmer *et al.*, 2011; Hilker *et al.*, 2010) is integral to better understanding the impacts of climate (CCP, 2011) and land-cover change (Environment Canada, 2011) on carbon sequestration at local to national scales. New carbon monitoring procedures are of national significance, as they can improve quality and reduce uncertainty in forest carbon reporting under Canada's obligations to the United Nations Framework Convention on Climate Change (CCP, 2011; Environment Canada, 2011).

The Boreal Ecosystem Research and Monitoring Sites (BERMS), located in the southern boreal forest, Saskatchewan, (Figures 1 and 4) were founded, in part, by the Boreal Ecosystems Atmosphere Study (Baldocchi *et al.*, 1997; Sellers *et al.*, 1997) and continued from 2001 to 2011 as part of a synthesized effort to better understand the impacts of climate change and disturbance on the carbon cycle of terrestrial ecosystems (Fluxnet-Canada, Canadian Carbon Program) (Barr *et al.*, 2004; Margolis *et al.*, 2006; CCP, 2011). BERMS includes mature aspen (*Populus tremuloides*), black spruce (*Picea mariana*), a jack pine (*Pinus banksiana*) chronosequence (four stands), peatland, and burned sites.

ALS data were acquired in 2005, 2008, and 2011 (Figure 4a) to quantify the impacts of land surface heterogeneity on remote sensing-based inputs (primarily MODerate resolution Imaging Spectroradiometer (MODIS) land-cover products) to land surface models and EC estimates of net ecosystem exchange. Specifically, the ALS data are being used to: (a)

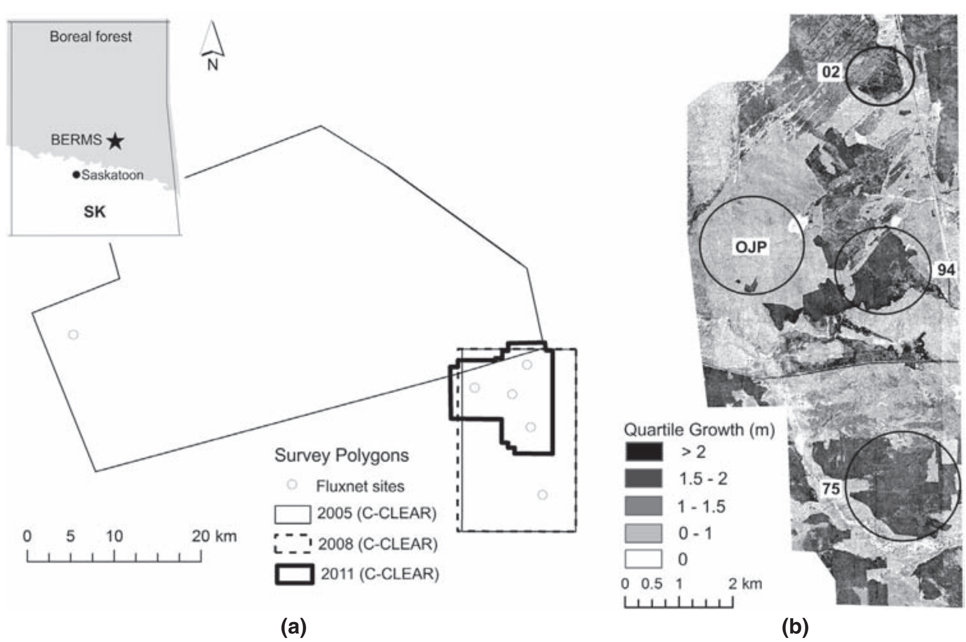

Figure 4. (a) ALS survey locations for BERMS in 2005, 2008, and 2011 (Inset: Saskatchewan location map), (b) ALS observations of stand growth from 2005 to 2011 for the chronosequence of harvested jack pine sites; OJP = "Old Jack Pine"; 75, 94, and 02 indicate year of harvest.

characterize canopy structure and topography within the EC field of view (or "footprint") (Kljun *et al.*, 2004; Chasmer *et al.*, 2008b), (b) assess MODIS within pixel heterogeneity and its influence on ecosystem productivity (Chasmer *et al.*, 2008a and 2009), (c) evaluate the spatio-temporal correspondence of canopy attributes within MODIS pixels to those of EC flux footprints (Chasmer *et al.*, 2011), and (d) quantify growth (Figure 4b) and develop an above-ground carbon mass balance monitoring procedure that integrates EC CO_2 flux observations with ALS growth measurements (Hopkinson *et al.*, 2012). Combined, the BERMS studies provide operational templates for scaling CO_2 flux observations and plot-level biomass estimates to the ecosystem-level and for calibrating satellite image data products.

Alberta Forest Hydrometeorology and Disturbance Monitoring

The Hydrology, Ecology and Disturbance (HEAD) project, located within the Western Boreal Plain (WBP) ecozone of north central Alberta (Figures 1 and 5) integrates time series ALS data, hydro-meteorological measurements, and field plots across a range of disturbed and natural landscapes. The WBP is a complex mosaic of peatlands, ponds, riparian buffers, and mixed-wood/aspen (*Populus tremuloides)* uplands, and is sensitive to oil/gas extraction, harvesting, fire, insect and climate-induced disturbances, which impact water and CO_2 fluxes (Devito *et al.*, 2005). The over-arching objective of HEAD is to study spatial interconnections between forest and wetland systems and their response to disturbance. The project provides recommendations to mitigate negative impacts from major disturbances, such as those resulting from fire, resource extraction or forest management practices.

C-CLEAR-supported surveys within the HEAD study area were conducted in 2002 and 2011, whereas the Government of Alberta commissioned surveys during 2006 to 2008 (Figure 5a). Coverage for 2002 was ~250 km² and for 2011 a combined ALS/thermal imaging survey covered ~50 km² of recently burned forest and peatland landscape. Baseline studies used the 2002 data to investigate uncertainties in ALS-based estimates: (a) vegetation canopy height and volume (Hopkinson *et al.*, 2005), and (b) terrain depressions (Lindsey and Creed, 2005). During this period, hydro-meteorological measurements, leaf area transects, and PSPs were monitored (Devito *et al.*, 2005). The interactions within and between land-cover types before and after disturbance have been recorded using a series of tower-based energy balance and EC measurements (Petrone *et al.*, 2007; Brown *et al.*, 2010). The influence of land surface changes on water and CO_2 fluxes have been studied by integrating ALS canopy and hydro-meteorological data (Chasmer *et al.*, 2011), whereas peatland and forest biomass loss due to fire is being quantified by integrating temporal ALS data (Figure 5b and 5c) with thermal and spectral imagery (Petrone *et al.*, 2012).

NWT ALS and Satellite Data to Support Remote FRI

The forested area of the Canadian Northwest Territories (NWT) is a remote land mass 33 million ha in size (Natural Resources Canada, 2011). Current inventory information covers <10 percent of its forests and more complete information on the forest resource is needed (Smith, 2002). To complement existing FRI information, circa 2000, federal and territorial government agencies completed a satellite-based land-cover map of the NWT (updated in 2007) under a project called the Earth Observation for the Sustainable Development of Forests (EOSD) (Wulder *et al.*, 2008b). To improve its utility, particularly for FRI, more structural data describing stand height, crown closure, volume, and aboveground biomass was needed. Based on federal and territorial reporting needs, an area of 200,000 km² comprising ~76 percent of the most timber productive forests within the southern Taiga Plains Ecozone (Ecosystem Classification Group, 2007) was identified for more intensive study (Figure 6).

ICESAT is a satellite that carries the Geoscience Laser Altimeter System (GLAS), a large footprint full waveform lidar sensor (Schutz *et al.*, 2005). GLAS orbital tracks range from

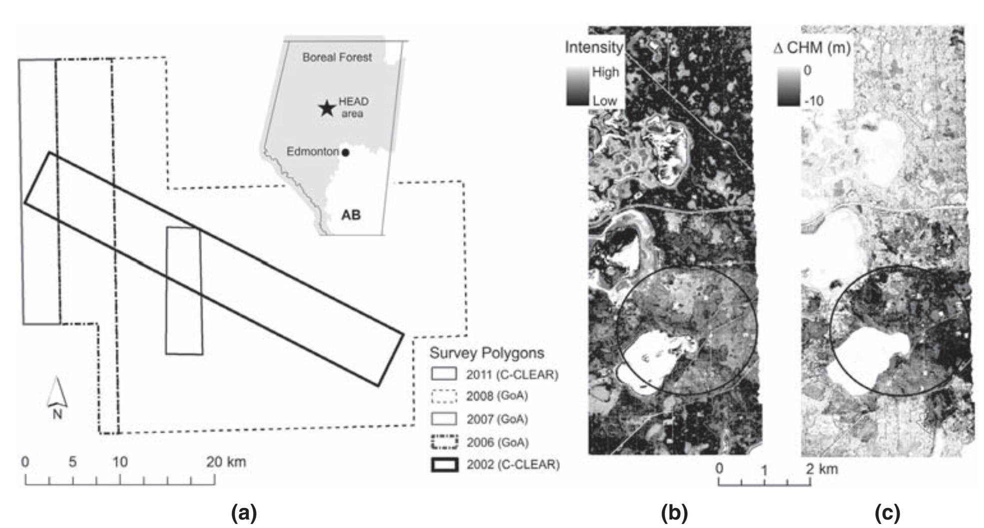

Figure 5. (a) HEAD study area illustrating ALS data collections from 2002 to 2011 (Inset: Alberta location map); (b) Intensity image captured in 2011 over mixed forest and peatland. Burn area (circled) stands out as an area of higher signal intensity, which is because foliage was lost to fire so laser pulses are not attenuated before reaching ground level; and (c) Canopy height change from 2008 to 2011 illustrates losses over burn area.

7 to 10 km apart in the NWT with footprint diameters of 60 to 65 m separated ~170 m along each track. The extraction of forest structure attributes from GLAS has been actively studied across a range of ecosystems (Harding and Carabajal, 2005; Lefsky *et al.*, 2005; Rosette *et al.*, 2008; Xing *et al.*, 2010; Miller *et al.*, 2011; Simard *et al.*, 2011). This requires the development of empirical models to relate GLAS waveforms of vegetation canopy profiles to field measurements of stand parameters. In the NWT (Figure 6), access difficulties limit field plot sampling at GLAS footprint locations so a contiguous sample of ALS data was acquired in 2007 (with supplementary data in 2008 and 2010) to facilitate a model calibration scaling process from field plot to ALS to GLAS waveform.

Discussion

In almost all cases, projects supported using the C-CLEAR approach were possible because costs, mission planning and field logistical responsibilities were shared among several partners. Although each project often had unique objectives and stakeholders, the procedures adopted across the complete ALS workflow (from planning to data modeling) demonstrated overlap. This collaborative approach to national research-based data collection has resulted in extensive knowledge transfer throughout the ALS and forestry communities (Table 1). Furthermore, this community development of ALS research and operational procedures has provided a basis for future standardization initiatives. The discussion illustrates how case studies have contributed to procedural and best practice development. Initially, we focus on the ALS workflow, with sections addressing data acquisition and processing. This is followed by sections dealing with the primary forest application domains supported: i.e., inventory, monitoring, and satellite data calibration.

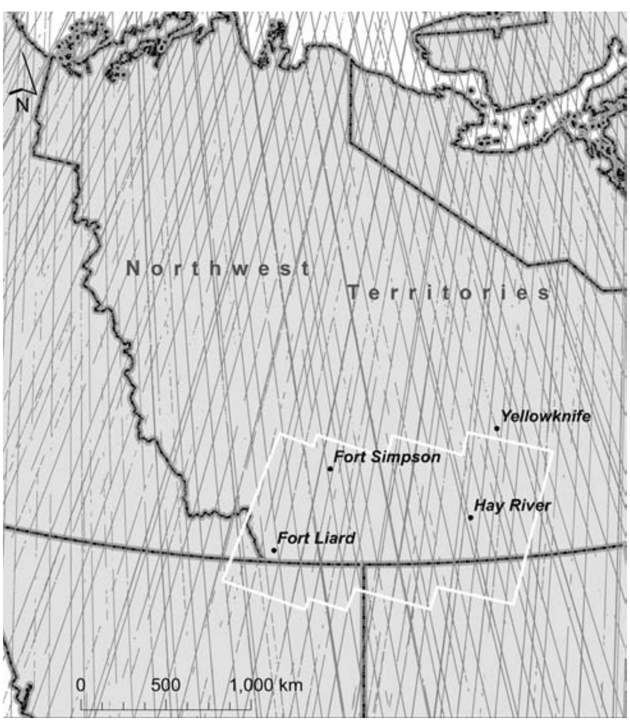

Figure 6. Schematic representation of ICESAT-GLAS orbital tracks over northern Canada with area of interest highlighted in white. ALS polygons surveyed near Fort Simpson and Hay River, with sample transect coverage near to Fort Liard and across to Yellowknife.

Mission Planning and Data Collection

At the outset of planning an ALS campaign a choice must be made whether to adopt a polygon ("wall to wall") or sample transect design. Landscape heterogeneity paired with the size of the area of interest determine whether polygon surveys are feasible or sampling transects are a necessity. For the relatively focused studies in Alberta, Saskatchewan, Ontario, and Quebec, where land surface heterogeneity is high and the emphasis is on understanding landscape processes and interactions, polygon coverage of the study sites was essential. However, for the large-scale studies initiated in Nova Scotia, Newfoundland, and NWT, where the focus is on inventory and reporting of forest attributes over thousands of square kilometers, transect sampling is optimal given cost and time constraints. A limitation is that large FRI stands may be inadequately represented using a transect approach, so for these case studies, polygon datasets were also captured to facilitate hierarchical modeling from plot to stand to province (Hopkinson *et al.*, 2011a).

As with other studies (Magnussen *et al.*, 2007; Næsset, 2009), C-CLEAR projects have demonstrated that variations in ALS survey configurations can alter the point cloud frequency distribution characteristics that are employed in many canopy attribute models (Chasmer *et al.*, 2006; Hopkinson, 2007). Such errors are problematic, for example, if the intent is to employ ALS-based monitoring of growth and yield (Yu *et al.*, 2006). There are many choices to be made before executing an ALS data acquisition. Timing, flying envelope (e.g., altitude, line spacing, velocity), ALS sensor settings (e.g., PRF and power, scan angle), placement of ground control can be optimized according to land surface characteristics and end-user needs. However, there is a wide range of evolving ALS sensor capabilities, which makes it challenging to specify standards in all but the most obvious cases, such as flying during leaf off and dry conditions for terrain mapping or full foliage for canopy modeling. However, with increased understanding of canopy laser pulse interactions (Morsdorff *et al.*, 2008; Næsset, 2009) it is possible to run point cloud simulations of canopy environments based on tunable acquisition settings and assumed canopy attributes (Goodwin *et al.*, 2007).

In the Quebec case study, voxel tree models positioned according to known characteristics of real trees measured at field plots are shot with simulated laser pulses fired according to actual flight trajectories recorded during an aerial survey (Figure 7). The simulated and observed point clouds are compared to calibrate the simulator. Once calibrated, the simulator creates point clouds mimicking a range of forest structures by planting voxel trees and simulating a range of survey configurations. The simulations can be analyzed to better understand how the point cloud varies with: (a) forest structure, and (b) survey parameters. This research will ultimately support the optimization of ALS survey plans to meet FRI needs across a range of forest types.

The benefit of a planning simulation before acquisition is that key settings such as scan angle and PRF (and power) can be optimized to provide the desired point cloud geometry and density attributes in a cost-effective manner. Furthermore, data attributes such as point density determine point cloud information content. A rule of thumb adopted after many C-CLEAR acquisitions is that for stand- and plot-level analyses, a single swath emitted pulse density of 1 pt/m^2

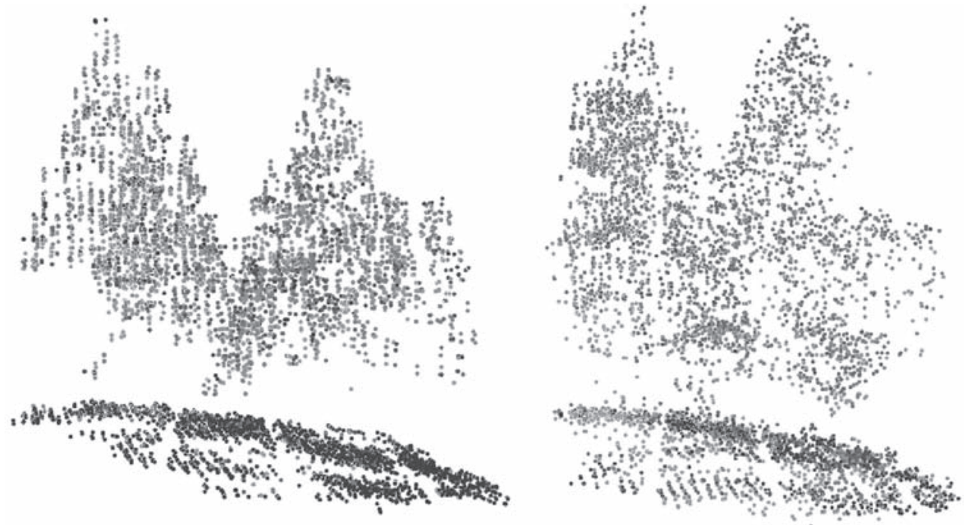

Figure 7. ALS point cloud simulated using voxel tree models and known survey parameters: (a) compared with the observed point cloud, and (b) Grey-scale represents the pulse return intensity. Note that although the simulated point cloud structure is close to reality, the ground return intensity is low and dead space between ground and canopy is slightly more pronounced than observed.

is sufficient for most basic modeling needs, because, for a typical 400 m^2 PSP or aggregated grid cell of 20 m × 20 m, this produces a minimum of 400 points for frequency distribution characterization. Under a typical 50 percent swath overlap scenario, with at least a first and last return per emitted pulse, this results in approximately 1,600 points per PSP or grid cell, which has proved adequate for modeling general characteristics of many forest canopies in Canada. This has been the approach in most C-CLEAR projects where the focus was large-area characterization at stand or landscape level. However, there is a growing tendency toward individual tree characterization, such as in the Quebec case study, where there is a need to optimize silvicultural practices at the tree level. In these cases, point densities approaching 10 pts/m^2 are more appropriate to ensure that there are sufficient points within each tree crown for adequate structural characterization.

The simplest way to control ALS point density is to vary the sensor PRF. However, increasing PRF reduces pulse power and return detection capability (Hopkinson, 2007). For typical applications, variations in pulse power have a minor impact on data quality, but in forested and wetland landscapes, these influences can be amplified. This was illustrated in the NWT case study over a vegetated wetland-dominated discontinuous permafrost landscape, where a small area was surveyed in 2007 and 2008. The survey and land surface attributes were comparable apart from the ALS system laser power being degraded in 2007, whereas in 2008, the sensor was operating optimally. In Figure 8 the reduced laser power in 2007 coincides with a low quality "noisy" digital elevation model (DEM) (RMSE 0.5 m) relative to 2008 (RMSE 0.2 m). Both DEMs underwent equivalent processing so the degraded laser power caused the increased noise. Weaker laser pulses encountered comparatively greater levels of interference from dense ground covers combined with increased signal loss due to high surface moisture content (Garroway *et al.*, 2011). It is valuable to catalog these operational consequences in remote landscapes, so that they can be mitigated at the project planning stage.

Data Processing and Modeling

In ALS forest attribute model development, there is a tendency to limit the number of point cloud metrics to two uncorrelated height- and ratio-based variables (Coops *et al.*, 2007; Parker and Evans, 2009; Magnussen *et al.*, 2010). Furthermore, there is little publicly available software that integrates all common steps in the associated workflows. This has forced users to string together several software packages or to develop in-house solutions, thus creating barriers to adoption and productivity. Given procedures to support ALS-based forest modeling have similarities despite differing geographies, there is an argument for standardization of workflow elements associated with points processing to model implementation.

All of the case studies summarized involve complex data-processing workflows to transform raw point clouds to modeled data products. This is true of the Newfoundland, Nova Scotia (Hopkinson *et al.*, 2011a), NWT, and the CFS national transect (Hopkinson *et al.*, 2011b; Wulder et al., 2012) projects where ALS-based models of canopy attributes need to be calibrated and applied over large areas. Given limited off-the shelf options, it was necessary to develop customized solutions. The challenge was to develop tools that were easily implementable yet generic enough for a range of forest-related applications. It was decided to customize an existing lidar processing tool suite, Pulse, developed by Gaimatic's Inc. (Lawrencetown, Nova Scotia). The workflow procedures assume that a user has been delivered calibrated but unclassified ALS strips in LAS binary (*http://www.asprs.org/Committee-General/LASer-LAS-File-Format-Exchange-Activities.html*) format and the data need to be outputted in raster tiles of point cloud metrics.

Pulse performs several automated sequential steps to batches of input files: (a) Segmentation of long corridor LAS

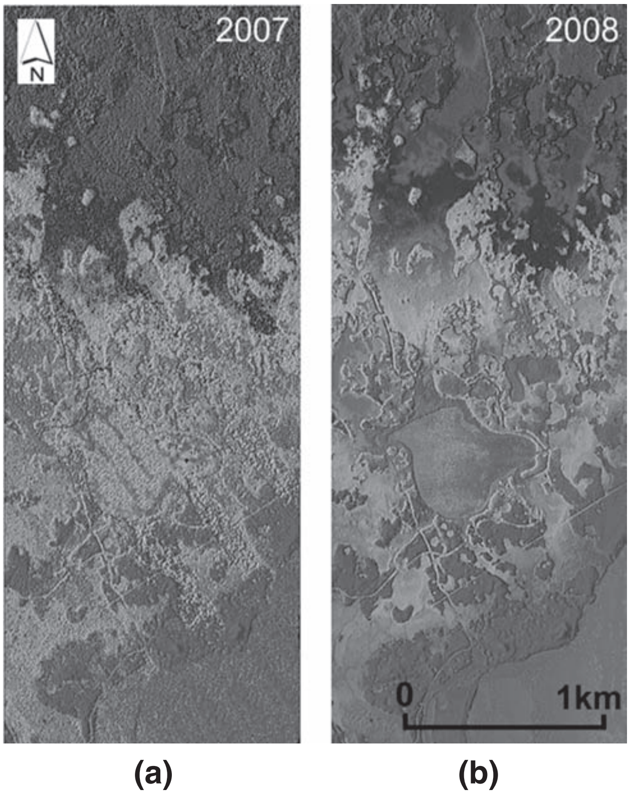

Figure 8. Comparison of enhanced hillshades of ALS DEMs collected over a fragmented forest-, bog- and fen-dominated site within the Taiga Plains discontinuous permafrost zone of the NWT. In (a) 2007, reduced laser power, high ground-level moisture and dense vegetation produced a noisy DEM. This is contrasted by (b) the high quality DEM obtained 12 months later from an equivalent survey but at higher laser power.

data files into regions containing approximately 10 million points including a small amount of overlap to avoid seam-lines when data are subsequently merged, (b) Data cleaning is achieved using a number of point filtering routines (e.g., isolate, low, high, etc.) to remove errors such as atmospheric scattering or multi-path, (c) Ground classification uses a variant of the popular ground filtering algorithm developed by Axelsson (1999), (d) Gridding of raster DEMs, shaded reliefs, canopy height models, data density grids (pts/m^2), and (e) Derivation of plot- or stand-level statistical point cloud and raster metrics similar to those generated by FUSION (McGaughey, 2010). To complete the forest attribute prediction workflow, the next step is to integrate into Pulse a user-defined model algorithm input combined with a metric selection procedure.

Commercial Forest Inventory

ALS-supported forest inventory is a rapidly growing application area but consensus is limited concerning integration and quality control procedures (Magnussen *et al.*, 2007), and there is a need for guidelines about what constitutes useful and valid ALS model calibration data (Coops *et al.*, 2007; Wulder *et al.*, 2008a; Zhao and Popescu, 2009). This is particularly important if inventory data are to be used in national reporting or long-term monitoring where different personnel or jurisdictions may have to make these kinds of subjective choices (Wulder *et al.*, 2004; Magnussen *et al.*, 2010).

Forest inventory objectives link the Newfoundland, Nova Scotia, Quebec, Saskatchewan, and NWT projects spanning multiple scales from hundreds of ALS points per tree to widely spaced ICESAT-GLAS footprints distributed across vast and remote areas. An approach has emerged for forest attribute modeling that uses ALS data as an intermediary calibration step between field plot and regional coverage (Hopkinson *et al.*, 2011a). In situations where tree-level structure characterization is necessary for fiber quality modeling (Newfoundland) and silvicultural management optimization (Quebec), it is becoming common to collect TLS data at the plot-scale (Côté *et al.*, 2011) to calibrate ALS landscape-scale models at a grid-cell size comparable to the area covered by field plot.

Forest attribute modeling to support provincial- and national-scale inventory requires attention to quality control procedures when combining plot- and stand-level calibration data with spatially coincident ALS point cloud metrics. As with many large-scale projects, the Nova Scotia biomass inventory would not have been feasible if plot and stand validation data had to be collected coincident to ALS surveys. Consequently, the provincial PSP and FRI databases were used, as the spatial cover and representation was ideal (Townsend, 2008). However, PSP data are revisited on a five-year rotation, whereas FRI metrics are updated from aerial photography approximately every ten years. This leads to temporal latency between ALS collection and the PSP or stand polygon datasets used for model calibration and simulation.

Of 3,250 provincial PSPs, 281 were spatially coincident with ALS data. After iterative biomass model training attempts using PSP biomass and ALS height and density metrics, model fit never exceeded an r^2 of 0.5. It was found that a temporal buffer of two years between PSP and ALS measurements was needed to ensure a degree of temporal consistency and minimize uncertainty. Consequently, 99 PSPs were "culled" improving ALS stem biomass model fit to an r^2 of 0.75. As with the PSPs, temporal latency compounded model uncertainties when applying the ALS model to FRI stand data. In extreme cases, there was up to 20 years separating FRI and ALS data. A ten-year buffer was applied and training data were culled by removing all ALS mean maximum and FRI mean stand heights of <5 m (note: ALS and FRI height metrics are expected to correlate but not equate). This procedure did not improve height model fit but did shift it closer to unity (Figure 9.), and ensured that areas of young growth or recent clearcut did not unduly bias model construction.

Growth and Disturbance Monitoring

When comparing temporally distinct ALS datasets captured and processed using inconsistent methods, it cannot be concluded with certainty that observed differences represent real changes in the landscape (Hopkinson *et al.*, 2008). It is clear that some standardization of acquisition and processing (discussed above) would mitigate uncertainties in temporal comparisons. It is also clear that given the high resolution, ALS data have a limited shelf-life in terms of representing "today's" land surface conditions and needs periodic collection for growth monitoring and disturbance assessment. However, it is unclear what time intervals are appropriate for ALS monitoring across Canadian forest species and ecozones.

The simplest change-monitoring scenario is that of a widespread "event" that can be characterized by comparing a "before" and "after" dataset. In a forested context, examples include sub-canopy snowpack mapping (Hopkinson *et al.*, 2004), defoliation following insect attack (Solberg and

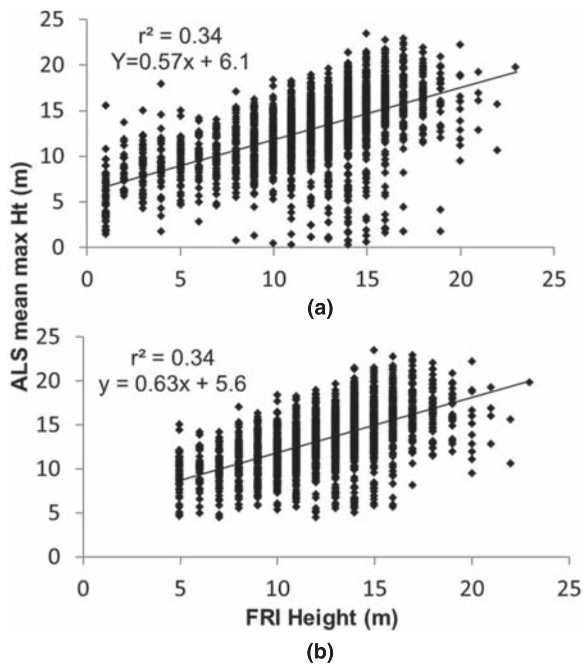

Figure 9. Mean maximum 20 m ALS grid cell height against FRI mean stand height: (a) Complete dataset (n = 2,639), and (b) culled dataset after removing all data <5 m (n = 2,340).

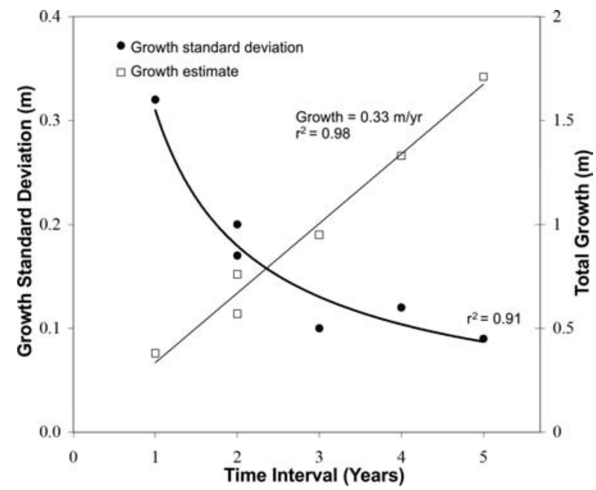

Figure 10. Observed conifer plantation growth and associated growth uncertainty (standard deviation) over a five year period (adapted from Hopkinson et al. (2008)).

Næsset, 2007), and fire, as was the case at the HEAD site. In most monitoring cases, care is needed to ensure point cloud attributes are comparable, as derived canopy height (Chasmer *et al.*, 2006; Hopkinson, 2007, Næsset, 2009) and cover (Hopkinson and Chasmer, 2009) metrics may contain bias, thus contaminating the true change in the landscape.

The observation of forest growth using ALS has been demonstrated (St-Onge and Vepakomma, 2004; Næsset and Gobakken, 2005; Yu *et al.*, 2004 and 2006) but standards describing a suitable monitoring interval for accurate growth measurement are lacking. From the Ontario case study, it was found that growth within a mature conifer plantation can be measured with a high degree of confidence after three years (Figure 10) if growth exceeds 0.3 m/year (Hopkinson *et al.*, 2008). Over six years, growth averaging between 0.1 m and 0.2 m/year was evident at the BERMS chronosequence sites (Figure 4b). From this limited sample and knowledge that ALS height data are typically precise to the decimeter-level, a rule of thumb is that if point density is ~1 pt/m^2, the growth rate for continuous conifer canopies can be accurately estimated if the repeat interval is sufficiently long that the observed cumulative growth exceeds ~0.5m. Consequently, whereas three years is the minimum for a mature conifer stand in the southern Ontario Mixed Wood Plains ecozone, an interval exceeding five years is required in the central Boreal Shield ecozone.

Another evolving procedural standard that builds upon the BERMS and HEAD case studies, is that of monitoring ecosystem productivity and landscape carbon fluxes by integrating ALS, satellite image, hydrometeorology and EC data (Chasmer *et al.*, 2008b, 2009, and 2011; Xiao *et al.*, 2012). Using ALS data to characterize ecosystem heterogeneity and within flux footprint biomass attributes through time, changing forest canopy attributes can be directly correlated with time-variant and cumulative EC CO_2 flux. These methods have been pioneered at the BERMS sites and are now being used for similar carbon assessment activities across Europe (Natascha Kljun, personal communication) and Australia (e.g., van Gorsel *et al.*, 2011; Hopkinson *et al.*, 2012).

Satellite Data Product Calibration

The United Nations Framework Convention on Climate Change is an international agreement that requires countries to monitor and report on forest carbon stocks or stock changes, including all emissions by sources and removals by sinks from managed lands (Intergovernmental Panel on Climate Change (IPCC) 2006; Kurz *et al.*, 2009). Actions that increase carbon stocks could mitigate climate change and the ability to assess trends in emissions and removals helps determine the future role of Canada's forests in the global carbon cycle (Natural Resources Canada, 2011). Given Canada's large size, satellite image products can be combined with carbon budget (Kurz *et al.*, 2009) and land surface model results (Arain *et al.*, 2006) to meet these reporting and management needs. However, forest heterogeneity exacerbates uncertainties in land surface models using low-resolution spectral remote-sensing products as data inputs (Chasmer *et al.*, 2011), and ICESAT-GLAS estimates of canopy height are compromised if the footprint overlies variable topography (Lee *et al.*, 2011). To mitigate the inherent uncertainties within low-resolution satellite data products, ALS data are increasingly being used as a means to calibrate or correct these model inputs. For example, successful empirical area-based ALS calibrations at the BERMS sites have been performed for MODIS fractional cover (Chasmer *et al.*, 2008a) and GLAS canopy height attributes (Los *et al.*, 2012).

In the NWT study, a more sophisticated topographic correction procedure was applied to GLAS data to derive more consistent waveform metrics for stand attribute modeling using a Geometric Optical-Radiative Transfer (GORT) model (Yang *et al.*, 2011). The adjusted r^2 for initial models for stand height, volume, and biomass ranged from 0.80 to 0.83 with RMSE values of 1.4 m, 16 m^3/ha, and 10 t/ha, respectively. These models produce point estimates of stand attributes that are being used in a k-Nearest Neighbor spatial imputation algorithm. This procedure generates spatial stand attributes that will be linked to the EOSD land-cover map (Wulder *et al.*, 2008b) to support a new satellite-based FRI. By using ALS data as an intermediate step in the calibration of GLAS data, forest structure, volume, and aboveground biomass can be mapped in northern boreal forest areas where more conventional air photo-based FRI would have been cost-prohibitive.

Conclusions

It is clear in the forestry community that ALS data can be used to directly derive a range of useful data products or as input to models that are used to support management and planning decisions. However, the procedures for acquiring data and converting to high quality, consistent and widely applicable information across the range of forest stakeholder communities in Canada lack standardization. Although examples of gradual best practice adoption in the forest sector have been illustrated here, future efforts need to be directed explicitly toward the task of procedural standardization so that the benefits can be maximized for all stakeholders. A recommendation of this paper is that an institute be set up dedicated to the tasks of researching and implementing guidelines, standards, certifications, and accredited training to meet the needs of the ALS community.

Such an Institute could borrow from the lessons learned after the decade of centrally coordinated consortium research support through C-CLEAR. Specifically, the resources to support and coordinate the institute activities could be hosted either by one university or a network of universities but must be available to the national community. While C-CLEAR tended to support academic and government activities, many projects involved close collaboration with the private sector: both in terms of resource sharing and two-way knowledge transfer. Furthermore, professional societies play a key role in information dissemination and community guidance/oversight. A Lidar Institute must embrace connectivity with all four communities to leverage the knowledge and resources of each: i.e., academia to support research and training; government to represent policy, planning and management needs; industry to inform on operational procedures and technology developments; and professional societies to assist with outreach and the brokerage of certifications and accreditations.

Acknowledgments

The following individuals are acknowledged either for their significant support for the case studies and/or in the development of C-CLEAR: Alain Pietroniro (Water Survey of Canada), Michael Demuth (Geological Survey of Canada), Michael Sitar and Jim Green (Optech, Inc.), Paul Treitz and Harry McCaughey (Queen's University), Robert Maher, Chris Beasy, Sue Monette and Danik Bourdeau (AGRG), Michael Wulder and Michelle Filiatrault (Canadian Forest Service), Nicholas Coops (University of British Columbia), Wade Bowers (Grenfell Campus, Memorial University), Allyson Fox, Heather Morrison and Neville Crasto (Acadia University), Tristan Goulden (Dalhousie University), Irena Creed (University of Western Ontario), Kevin Devito (University of Alberta), Scott Brown and William Quinton (Wilfrid Laurier University), Barry White and John Diiwu (Alberta Sustainable Resources Development), John Pomeroy (University of Saskatchewan), Jean Bégin and Jean-Claude Ruel (University of Laval), Cristina Budei and Udaya Vepakomma (UQAM), Jean Francois Côté and Olivier van Lier (Canadian Forest Service), Natascha Kljun (University of Swansea), John Barlow (University of Sussex). The following institutions are acknowledged for providing financial or other material support either to C-CLEAR or the case studies presented: Optech, Inc., Queen's University, NS Community College, NS Department of Natural Resources, NS Power, Inc., Memorial University, Natural Resources Canada, Environment Canada, Parks Canada, University of Sherbrooke, University of Quebec at Montreal, SilvEcon, Inc., Fluxnet Canada, Canadian Carbon Program, Government of Alberta, Government of the Northwest Territories, Northern Oil and Gas Science Research Initiative of Indian and Northern Affairs Canada Airborne Imaging, Inc., Scotia Flight, Inc., Canada Foundation for Innovation, Natural Sciences and Engineering Research Council, UK Natural Environment Research Council, Canadian Foundation for Climate and Atmospheric Sciences, Fonds de Recherche Québécois sur la Nature et les Technologies, Canadian Wood Fibre Centre, Corner Brook Pulp and Paper Limited, FP Innovations, NL Department of Natural Resources, Atlantic Canada Opportunities Agency, Centre for Forest Science and Innovation, NL Department of Innovation, Business and Rural Development, and NL Research and Development Corporation.

References

Atlantic Provinces Economic Council (APEC), 2008. *Building Competitiveness in Atlantic Canada's Forest Industries: A Strategy for Future Prosperity*, APEC, Halifax, Nova Scotia. 75 p.

Arain, M.A., F. Yuan, and A.T. Black. 2006. Soil-plant nitrogen cycling modulated carbon exchanges in a western temperate conifer forest in Canada, *Agricultural and Forest Meteorology*, 140:171–192.

Axelsson, P. 1999. Processing of laser scanner data - Algorithms and applications, *ISPRS Journal of Photogrammetry and Remote Sensing*, 54(2-3):138–147.

Baldocchi, D. 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future, *Global Change Biology*, 9:1-14.

Baldocchi, D.D., C.A. Vogel, and B. Hall, 1997. Seasonal variation of carbon dioxide exchange rates above and below a boreal jack pine forest, *Agricultural and Forest Meteorology*, 83:147–170.

Barr, A.G., T.A. Black, E.H. Hogg, N. Kljun, K. Morgenstern, and Z. Nesic, 2004. Inter-annual variability in the leaf area index of a boreal aspen-hazelnut forest in relation to net ecosystem production, *Agricultural and Forest Meteorology*, 126:237–255.

Brown, S. M., R. M. Petrone, C. Mendoza, and K. J. Devito, 2010. Surface vegetation controls on evapotranspiration from a subhumid Western Boreal Plain wetland, *Hydrological Processes*, 24:1072–1085.

Canadian Carbon Program (CCP), 2011. *Ecosystems in Flux: Carbon, Climate and Disturbance in Canadian Forests and Peatlands: Perspectives from the Fluxnet-Canada and Canadian Carbon Program Research Networks (2001-2011)* (C. Coursolle, editor), Canadian Carbon Program. Quebec, QB. Canada. 46 p.

Carey and Associates, 2009. *The Global Market for Airborne LiDAR Systems and Services*, URL: http://caryandassociates.com/about/releases/pr16.html, Carey and Associates, Longmont, Colorado (last date accessed: 19 November 2012).

Chasmer, L., C. Hopkinson, A. Barr, A. Black, H. McCaughey, and P. Treitz, 2009. Scaling and assessment of GPP from MODIS using a combination of airborne LiDAR and eddy covariance measurements over jack pine forests, *Remote Sensing of Environment*, 113:82–93.

Chasmer, L.E., C. Hopkinson, B. Smith, and P. Treitz, 2006. Examining the influence of changing laser pulse repetition frequencies on conifer forest canopy returns, *Photogrammetric Engineering & Remote Sensing*, 72(12):1359–1367.

Chasmer, L., C. Hopkinson, P. Treitz, H. McCaughey, A. Barr, and A. Black, 2008a. A LiDAR-based hierarchical approach to assessing MODIS fPAR, *Remote Sensing of Environment*, 112:4344–4357.

Chasmer, L., N. Kljun, A. Barr, A. Black, C. Hopkinson, H. McCaughey, and P. Treitz, 2008b. Vegetation structural and elevation influences on CO_2 uptake within a mature jack pine forest in Saskatchewan, Canada, *Canadian Journal of Forest Research*, 38:2746–2761.

Chasmer, L., N. Kljun, C. Hopkinson, S. Brown, T. Milne, K. Giroux, A. Barr, K. Devito, I. Creed, and R. Petrone 2011. Characterizing vegetation structural and topographic characteristics sampled by eddy covariance within two mature aspen stands using LiDAR and a flux footprint model: Scaling to MODIS, *Journal of Geophysical Research - Biogeosciences*, 116:G02026, 19 p.

Coops, N.C., T. Hilker, M. Wulder, B. St.-Onge, G. Newnham, A. Siggins, and J.A. Trofymow, 2007. Estimating canopy structure of Douglas-fir forest stands from discrete-return LiDAR, *Trees - Structure and Function*, 21(3):295–310.

Côté, J.-F., R.A. Fournier, J.E. Luther, and O.R. van Lier, 2010. Canopy structure characterization of balsam fir stands with terrestrial LiDAR and fine scale architectural modeling, *Proceedings of Silvilaser 2010, the 10th International Conference on LiDAR Applications for Assessing Forest Ecosystems*, 14-17 September, Freiburg, Germany, unpaginated USB drive.

Devito, K., I. Creed, T. Gan, C. Mendoza, R. Petrone, U. Silins, and B. Smerdon, 2005a. A framework for broad scale classification of hydrologic response units on the Boreal Plains: Is topography the last thing to think of?, *Hydrological Processes*, 19(8): 1705–1714.

Ecosystem Classification Group, 2007. *Ecological Regions of the Northwest Territories - Taiga Plains*, Department of Environment and Natural Resources, Government of Northwest Territories, Yellowknife, NT, Canada. Vii + 209 p. + folded insert poster map

Environment Canada, 2011. *National Inventory Report, 1990-2009: Greenhouse Gas Sources and Sinks in Canada, Executive Summary*, Public Works and Government Services of Canada, Ottawa, ON, 20 p.

Evans, J.S., T.A. Hudak, R. Faux, and A.M.S. Smith, 2009. Discrete return LiDAR in natural resources: Recommendations for project planning, data processing, and deliverables, *Remote Sensing*, 1:776–794.

Garroway, K., C. Hopkinson, and R. Jamieson. 2011. Investigating the influence of surface moisture and vegetation cover on airborne LiDAR intensity data, *Canadian Journal of Remote Sensing,* 37(3):275–284.

Goodwin, N.R., N.C. Coops, and D.S. Culvenor, 2007. Development of a simulation model to predict LiDAR interception in forested environments, *Remote Sensing of Environment*, 111(4):481–492.

Goulden, T., and C. Hopkinson, 2010. The forward propagation of integrated system components within airborne LiDAR data, *Photogrammetric Engineering & Remote Sensing*, 76(5):598–601.

Harding, D.J., and C.C. Carabajal. 2005. ICESat waveform measurements of within-footprint topographic relief and vegetation vertical structure, *Geophysical Research Letters*, 32:L21S10, 4 p.

Heidemann, K., 2011, The USGS-NGP LiDAR guidelines and base specification. *Proceedings of the U.S. Geological Survey Eighth Biennial Geographic Information Science Workshop and The First National Map Users Conference* (J.B. Sieverling and J. Dietterle, editors), Denver, Colorado, 10-13 May, U.S. Geological Survey Scientific Investigations Report, 2011–5053.

Hilker, T., F.G. Hall, N.C. Coops, A. Lyapustin, Y. Wang, N. Grant, Z. Nesic, T. A. Black, M. Wulder, N. Kljun, L. Chasmer, C. Hopkinson, 2010. Remote sensing of photosynthetic light use efficiency across two forested biomes (1): Spatial scaling, *Remote Sensing of Environment.* 114:2863–2874.

Hopkinson, C., 2007. The influence of flying altitude and beam divergence on canopy penetration and laser pulse return distribution characteristics, *Canadian Journal of Remote Sensing*, 33(4):312–324.

Hopkinson, C., and L. Chasmer, 2009. Testing LiDAR models of fractional cover across multiple forest ecozones, *Remote Sensing of Environment.*113:275–288.

Hopkinson, C., L. Chasmer, and R.J. Hall, 2008. Using airborne LiDAR to examine forest growth, *Remote Sensing of Environment,* 112(3):1168–1180.

Hopkinson C, L. Chasmer, N. Kljun, E. van Gorsel, H. McCaughey, A. Barr, A. Black, 2012. ALS monitoring of changes in above ground forest carbon storage, *Proceedings of the SilviLaser 2012 Conference*, 16-19 September, Vancouver, Canada, unpaginated USB drive.

Hopkinson, C., L.E. Chasmer, G. Zsigovics, I. Creed, M. Sitar, W. Kalbfleisch, and P. Treitz, 2005. Vegetation class dependent errors in LiDAR ground elevation and canopy height estimates in a Boreal wetland environment, *Canadian Journal of Remote Sensing*, 31(2):191–206.

Hopkinson, C., D. Colville, D. Bourdeau, S. Monette, and R. Maher, 2011a. Scaling plot to stand-level LiDAR to public GIS data in a hierarchical approach to map forest biomass, *Proceedings of the SilviLaser 2011 Conference,* 16-20 October, Hobart, Tasmania, unpaginated USB drive.

Hopkinson, C., and R. Maher, 2009. Meeting LiDAR industry and end-user needs: Best practice guidelines, skills training and efficient project design, *Proceedings of the 9th International Lidar Mapping Forum,* New Orleans, Louisiana, February, Unpaginated CD-ROM.

Hopkinson, C., M. Sitar, L.E. Chasmer, and P. Treitz, 2004. Mapping snowpack depth beneath forest canopies using airborne LiDAR, *Photogrammetric Engineering & Remote Sensing*, 70(3):323–330.

Hopkinson, C., M.A. Wulder, N.C. Coops, T. Milne, A. Fox, C.B. Bater, 2011b. Airborne LiDAR sampling of the Canadian boreal forest: Planning, execution & initial processing, *Proceedings of the SilviLaser 2011 Conference*, 16-20 October, Hobart, Tasmania, unpaginated USB drive.

Hudak, A.T., J.S. Evans, and A.M.S. Smith. 2009. LiDAR utility for natural resource managers, *Remote Sensing*, 1:934–951.

Huh, K., B. Mark, C. Hopkinson, 2012. Changes of topographic context of the Yanamarey glacier in the Tropical Peruvian Andes, *Proceedings of the International Remote Sensing Hydrology Symposium* (C. Neale and R. Gerber, editors), Jackson Hole, Wyoming 25 September, IAHS Redbook publication 352, 4 p.

Intergovernmental Panel on Climate Change (IPCC), 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Prepared by the National Greenhouse Gas Inventories Programme (H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, editors), IGES, Japan, URL: *http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html* (last date accessed: 19 November 2012.

Johansen K, N.C. Coops, S.E. Gergel, Y. Stange, 2007. Application of high spatial resolution satellite imagery for riparian and forest ecosystem classification, *Remote Sensing of Environment*, 110:29–44.

Kljun, N., P. Calanca, M. Rotach, and H. Schmid, 2004. A simple parameterisation for flux footprint predictions, *Boundary Layer Meteorology*, 112:503–523.

Kurz, W.A., C.C. Dymond, T.M. White, G. Stinson, C.H. Shaw, G.J. Rampley, C.Smyth, B.N. Simpson, E.T. Neilson, J.A. Trofymow, J. Metsaranta, M.J. Apps, 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards, *Ecological Modeling*, 220:480–504.

Lambert, M.-C, C.H. Ung, and F. Raulier, 2005. Canadian national tree aboveground biomass equations, *Canadian Journal of Forest Research*, 35:1996–2018.

Landsberg, J.J., and R.H. Waring, 2004. Top-down models and flux measurements are complementary methods of estimating carbon sequestration by forests: Illustrations using the 3-PG model, *Forests at the Land–Atmosphere Interface* (M. Mencuccini, J. Grace, and K.G. McNaughton, editors). CABI Publishing, Cambridge, Massachusetts, pp 37–50.

Lee, S., W. Ni-Meister, W. Yang, and Q. Chen, 2011. Physically based vertical vegetation structure retrieval from ICESat data: Validation using LVIS in White Mountain National Forest, New Hampshire, USA, *Remote Sensing of Environment*, 115:2776–2785.

Lefsky M.A., W.B. Cohen, G.G. Parker, and D.J. Harding, 2002. LiDAR remote-sensing for ecosystem studies, *BioScience*, 52:19–30.

Lefsky, M.A., D.J. Harding, M. Keller, W.B. Cohen, C.C. Carabajal, F. Del Bom Espirito-Santo, M.O. Hunter, and R. de Oliveira Jr., 2005. Estimates of forest canopy height and aboveground biomass using ICESat, *Geophysical Research Letters*, 32:L22S02, 6 p.

Lim, K., C. Hopkinson, and P. Treitz, 2008. Examining the effects of sampling point densities on laser canopy height and density metrics at the forest plot level, *Forestry Chronicle*, 84(6):876–885.

Lim, K., P. Treitz, M.A. Wulder, B. St-Onge, and M. Flood. 2003. LiDAR remote-sensing of forest structure, *Progress in Physical Geography*, 27:88–106.

Lindsey, J., and I. Creed, 2005. Sensitivity of digital landscapes to artifact depressions in remotely-sensed DEMs, *Photogrammetric Engineering & Remote Sensing*, 71(9):1029–1036.

Los, S.O., J.A.B. Rosette, N. Kljun, P.R.J. North, L. Chasmer, J.C. Suárez, C. Hopkinson, R.A. Hill, E. van Gorsel, C. Mahoney, and J. A. J. Berni, 2012. Vegetation height and cover fraction between 60° S and 60° N from ICESat and GLAS data, *Geoscientific Model Development Discussions*. 5:413–432.

Mackenzie, J., and G. Bruemmer, 2009. Enhancing Canada's forest fibre*, The Forestry Chronicle*, 85(3):353–354.

Magnussen, S., E. Næsset, and T. Gobakken, 2010. Reliability of LiDAR derived predictors of forest inventory attributes: A case study with Norway spruce, *Remote Sensing of Environment*, 114(4):700–712.

Magnussen, S., E. Næsset, and M.A. Wulder, 2007. Efficient multiresolution spatial predictions for large data arrays, *Remote Sensing of Environment*, 109(4):451–463.

Margolis, H., L. Flanagan, and B. Amiro, 2006. The Fluxnet-Canada research network: Influence of climate and disturbance on carbon cycling in forests and peatlands, *Agricultural and Forest Meteorology*, 140:1–5.

McGaughey, R.J., 2010. *Fusion/LDV: Software for LiDAR Data Analysis and Visualization*, USDA Forest Service, FUSION Manual, March 2010, FUSION version 2.80.

Miller, M.E., M. Lefsky, and Y. Pang, 2011. Optimization of Geoscience Laser Altimeter System waveform metrics to support vegetation measurements, *Remote Sensing of Environment*, 115:298–305.

Morsdorf, F., O. Frey, E. Mier, K.I. Iten, and B. Allgower, 2008. Assessment of the influence of flying altitude and scan angle on biophysical vegetation products derived from airborne laser scanning, *International Journal of Remote Sensing,* 29(5):1387–1406.

Næsset, E., 2009. Effects of different sensors, flying altitudes, and pulse repetition frequencies on forest canopy metrics and biophysical stand properties derived from small-footprint airborne laser data, *Remote Sensing of Environment*, 113(1):149–159.

Næsset, E., and T. Gobakken, 2005. Estimating forest growth using canopy metrics derived from airborne laser scanner data, *Remote Sensing of Environment*, 96:453–465.

Næsset, E., T. Gobakken, J. Holmgren, H. Hyyppä, M. Maltamo, M. Nilsson, H. Olsson, A. Persson, and U. Söderman, 2004. Laser scanning of forest resources: The Nordic experience, *Scandinavian Journal of Forest Research*, 19(6):482–499.

Natural Resources Canada, 2011. *The state of Canada's forests, annual report 2011*, Natural Resources Canada, Canadian Forest Service, Ottawa, Ontario. 48 p.

Nova Scotia Department of Energy (NSDE), 2010. *Renewable electricity plan: A path to good jobs, stable prices, and a cleaner environment*, Report published by the Government of Nova Scotia, Halifax, Nova Scotia. 32 p.

Parker, R.C., and D.L. Evans, 2009. LiDAR forest inventory with single-tree, double-, and single-phase procedures, *International Journal of Forestry Research,* 2009:864108, 6 p.

Petrone R.M., U. Silins, and K. J. Devito, 2007. Dynamics of evapotranspiration from a riparian pond complex in the Western Boreal Forest, Alberta, Canada, *Hydrological Processes*, 21(11):1391–1401.

Reutebuch, S., H. Anderson, and B. McGaughey, 2005. Light detection and ranging (LIDAR): An emerging tool for multiple resource inventory, *Journal of Forestry*, 9:286–292.

Rosette, J.A.B., P.R.J. North, and J.C. Suérez. 2008. Vegetation height estimates for a mixed temperate forest using satellite laser altimetry, *International Journal of Remote Sensing*, 29:1475–1493.

Schutz, B., H.J. Zwally, A. Shuman, D. Hancock, and J.P. DiMarzio. 2005. Overview of the ICESat Mission, *Geophysical Research Letters*, 32:L21S01 4 p.

Sellers, P.J., F.G. Hall, R.D. Kelly, A. Black, D. Baldocchi, J. Berry, M. Ryan, K.J. Ranson, P.M. Crill, D. Lettenmaier, H. Margolis, J. Cihlar, J. Newcomer, D. Fitzharrald, P.G. Jarvis, S.T. Gower, D. Halliwell, D. Williams, B. Goodison, D. Wickland, F.E. Guertin, 1997. BOREAS in 1997: Experiment overview, scientific results, and future directions, *Journal of Geophysical Research*, 102: 28731–28769.

Simard, M., N. Pinto, J.B. Fisher, A. Baccini, 2011. Mapping forest canopy height globally with spaceborne LiDAR, *Journal of Geophysical Research* 116:G04021 12 p.

Smith, L., 2002. *Forest Resource Inventory and Analysis Strategic Plan*, Government of Northwest Territories, Resources, Wildlife and Economic Development, Forest Management Division, Hay River, NWT.

Solberg, S., and E. Næsset, 2007. Mapping defoliation with LiDAR, *Proceedings of the SilviLaser Conference, 2007, Espoo, Finland,* 12-14 September, International Archives of Photogrammetry and Remote Sensing, XXXVI(3-W52):379–382.

St-Onge B., and U. Vepakomma, 2004. Assessing forest gap dynamics and growth using multi-temporal laser scanner data, *Proceedings of the Laser-Scanners for Forest and Landscape Assessment - Instruments, Processing Methods and Applications International Conference*, Frieburg im Breisgau, 03-06 October, pp. 173–178.

Townsend, P., 2008. *Forest Biomass of Living Merchantable Trees in Nova Scotia*, Report FOR 2008-9, Nova Scotia Department of Natural Resources, Government of Nova Scotia publication, Halifax, Nova Scotia.

van Gorsel, E., N. Kljun, R. Leuning, A.J. Berni, A. Cabello-Leblic, A. Held, V. Haverd, C. Hopkinson, L. Chasmer, and K Youngentob, 2011. Use of high resolution LiDAR and hyperspectral data to evaluate the sensitivity of net ecosystem exchange to stand structural and plant chemical properties, *Proceedings of the 34th International Symposium on Remote Sensing of Environment*, Sydney Australia, 10-15 April, URL: *http://www.isprs.org/proceedings/2011/ISRSE-34/211104015Final00381.pdf* (last date accessed: 19 November 2012).

Whalen, D., D.L. Forbes, C. Hopkinson, J.C. Lavergne, G.K. Manson, P. Marsh, S.M. Solomon, 2009. Topographic LiDAR - Providing a new perspective in the Mackenzie Delta, *Proceedings of the 30th Canadian Symposium on Remote Sensing*, Lethbridge, Alberta, June, unpaginated CDROM.

Woods, M., K. Lim, and P. Treitz, 2009. Predicting forest stand variables from LiDAR data in the Great Lakes - St. Lawrence Forest of Ontario, *Forestry Chronicle*, 84(6):827–839.

Woods, M., D. Pitt, M. Penner, K. Lim, D. Nexbitt, D. Etheridge, and P. Treitz, 2011. Operational implementation of a LiDAR inventory in Boreal Ontario, *The Forestry Chronicle*, 87(4):512–528.

Wulder, M.A., C.W. Bater, N.C. Coops, T. Hilker and J.C. White, 2008a. The role of LiDAR in sustainable forest management, *The Forestry Chronicle*, 84:807–826.

Wulder, M.A., R.J. Hall, N.C. Coops, and S.E. Franklin, 2004. High spatial resolution remotely sensed data for ecosystem characterization, *BioScience*, 54(6):511–521.

Wulder, M.A., J.C. White, C.W. Bater, N.C. Coops, C. Hopkinson, G. Chen, 2012. LiDAR plots - A new large-area data collection option: context, concepts, and case study, *Canadian Remote Sensing Journal*, 38(05):600–618.

Wulder, M.A., J.C. White, M. Cranny, R.J. Hall, J.E. Luther, A. Beaudoin, D.G. Goodenough, J.A. Dechka, 2008b. Monitoring Canada's forests, Part I: Completion of the EOSD land cover project, *Canadian Journal of Remote Sensing*, 34:549–562.

Xiao, J., J. Chen, K. Davis, and M. Reichstein, 2012. Advances in upscaling of eddy covariance measurements of carbon and water fluxes, *Journal of Geophysical Research*, 117:G00J01. 4 p.

Xing, Y., A. de Gier, J. Zhang, and L.Wang. 2010. An improved method for estimating forest canopy height using ICESat-GLAS full waveform data over sloping terrain: A case study in Changbai mountains, China, *International Journal of Applied Earth Observation and Geoinformation*, 12:385–392.

Yang,W., W. Ni-Meister, and S. Lee. 2011. Assessment of the impacts of surface topography, off-nadir pointing and vegetation structure on vegetation LiDAR waveforms using an extended geometric optical and radiative transfer model, *Remote Sensing of Environment*, 115:2810–2822.

Yu, X., J. Hyyppä, H. Kaartinen, and M. Maltamo, 2004. Automatic detection of harvested trees and determination of forest growth using airborne laser scanning, *Remote Sensing of Environment*, 90(4):451–462.

Yu, X., J. Hyyppä, A. Kuko, M. Maltamo, and H. Kaartinen, 2006. Change detection techniques for canopy height growth measurements using airborne laser scanner data, *Photogrammetric Engineering & Remote Sensing*, 72(12):1339–1348.

Zhao, K., and S. Popescu, 2009. LiDAR-based mapping of leaf area index and its use for validating GLOBCARBON satellite LAI product in a temperate forest of the southern USA, *Remote Sensing of Environment*, 113(8):1628–1645.