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Lidar plots — a new large-area data collection option: context, concepts, and case study

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Abstract. Forests are an important global resource, playing key roles in both the environment and the economy. The implementation of quality national monitoring programs is required for the generation of robust national statistics, which in turn support global reporting. Conventional monitoring initiatives based on samples of field plots have proven robust but are difficult and costly to implement and maintain, especially for large jurisdictions or where access is difficult. To address this problem, air photo- and satellite-based large area mapping and monitoring programs have been developed; however, these programs also require ground measurements for calibration and validation. To mitigate this need for ground plot data we propose the collection and integration of light detection and ranging (lidar) based plot data. Lidar enables accurate measures of vertical forest structure, including canopy height, volume, and biomass. Rather than acquiring wall-to-wall lidar coverage, we propose the acquisition of a sample of scanned lidar transects to estimate conditions over large areas. Given an appropriate sampling framework, statistics can be generated from the lidar plots extracted from the transects. In other instances, the lidar plots may be treated similar to ground plots, providing locally relevant information that can be used independently or integrated with other data sources, including optical remotely sensed data. In this study we introduce the concept of "lidar plots" to support forest inventory and scientific applications, particularly for large areas. Many elements must be considered when planning a transect-based lidar survey, including survey design, flight and sensor parameters, acquisition considerations, mass data processing, and database development. We present a case study describing the acquisition of over 25 000 km of lidar data in Canada's boreal forests in the summer of 2010. The survey, which included areas of managed and unmanaged forests, resulted in the production of more than 17 million 25 × 25 m lidar plots with first returns greater than 2 m in height. We conclude with insights gained from the case study and recommendations for future surveys.

Résumé. Les forêts constituent une ressource importante à l'échelle du globe, celles-ci jouant un rôle essentiel tant au niveau de l'environnement que de l'économie. La mise en place de programmes de suivi de qualité à l'échelle nationale est essentielle pour la production de statistiques nationales robustes qui en retour soutiennent les activités de diffusion des données (global reporting) à l'échelle du globe. Les initiatives conventionnelles de suivi basées sur des échantillons de placettes se sont avérées robustes, mais difficiles et coûteuses à mettre en place et à tenir à jour, spécialement pour les grandes unités administratives ou là où l'accès est difficile. Pour solutionner ce problème, on a développé des programmes de cartographie et de suivi à grande échelle basés sur l'utilisation des photographies aériennes et des données satellitaires; toutefois, ces programmes nécessitent aussi des mesures de terrain pour les besoins d'étalonnage et de validation. Pour répondre à ce besoin pour des données de placettes-échantillons, on propose la collecte et l'intégration de données lidar « light detection and ranging » au niveau des placettes. Le lidar permet d'acquérir des mesures précises de la structure verticale de la forêt incluant la hauteur, le volume et la biomasse du couvert. Plutôt que d'acquérir une couverture lidar mur à mur, on propose l'acquisition d'un échantillon de transects lidar scannés pour estimer les conditions sur de grandes étendues. En fonction d'un cadre approprié d'échantillonnage, des statistiques peuvent être générées à partir des parcelles lidar extraites des transects. Éventuellement, les placettes lidar peuvent être traitées comme des placettes-échantillons, celles-ci apportant alors une information locale

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pertinente pouvant être utilisée indépendamment ou intégrée avec d'autres sources de données dont des données optiques de télédétection. Dans cette communication, on présente le concept de "placettes lidar" en soutien aux inventaires forestiers et aux applications scientifiques, en particulier pour des grandes superficies. Plusieurs éléments doivent être pris en considération dans la planification d'un relevé de transect lidar incluant la conception du relevé, les paramètres du survol et du capteur, des considérations relatives à l'acquisition, le traitement d'information massive et le développement de la base de données. On présente une étude de cas décrivant l'acquisition de plus de 25 000 km de données lidar dans les forêts boréales du Canada durant l'été 2010. Le relevé, qui comprenait des zones de forêt aménagée et de forêt naturelle, a résulté dans la production de plus de 17 millions de placettes de 25 m par 25 m avec des premiers retours supérieurs à 2 m de hauteur. On conclut par des considérations dérivées de l'étude de cas et des recommandations pour des relevés futurs.
[Traduit par la Rédaction]

Introduction

Forests play an important role in providing economic and environmental goods and services, including building materials and fuel, wildlife habitat, the maintenance of biodiversity, the enabling of an exchange of gasses with the atmosphere, and carbon sequestration (Patterson et al., 2009). Globally, total forest area is estimated at just less than four billion hectares and represents 30% of total land area (FAO, 2006). Historically, forests have been managed from an economic perspective, with a focus on protection to enable long-term access to fibre, where limited annual levels of harvesting are typically followed by planting or monitored regeneration (Wulder et al., 2007a). This cycle of protection, harvesting, and planting is common in locations with sufficient access and productivity to enable growth of timber to merchantable quality and size over a reasonable regeneration time period, mediated by market demand. For locations with a lack of access and (or) low productivity, forests are often left to function naturally. Further, depending on a nation's level of development, forest inventory programs may not be well established or sufficiently institutionally engrained to promote the requisite level of regulation and monitoring.

Canada is steward to 10% of global forests (by cover), a resource that is managed for a suite of economic, social, and environmental values. A range of national programs have been developed to assess and monitor forests across Canada, including a National Forest Inventory (NFI), satellite-driven land cover and change (Earth Observation for Sustainable Development of forests, EOSD), and a Forest Carbon Accounting Program (FCAP). Common across these programs is a need for ground measures for calibration and validation. Much of Canada's forests, however, are remote and lack road access, precluding the installation of ground plots and the collection of ground data.

Plots remain the primary means for recording and reporting on forest conditions and are fundamental to many forest inventory programs. Permanent and temporary sample plots are used for many activities, including the development of growth and yield equations, reporting on forest conditions, and the calibration and validation of photo-based inventory data and of remotely sensed data and derivatives (Wulder et al., 2004). Permanent sample plots are remeasured every inventory cycle and are indispensable for change monitoring (Sayn-Wittgenstein and Aldred, 1976; Poso, 2006; Herold et al., 2011), while temporary sample plots are used to satisfy emerging or ad hoc information needs. The types of measures that may be made in situ (e.g., mensuration implemented during field plot visits) are difficult to accurately replicate using remote sensing (Wulder, 1998); however, new technologies, such as light detection and ranging (lidar), are enabling the estimation of a greater range of attributes with improved accuracy (Wulder et al., 2008a). Lidar is a remote sensing technology with a proven capacity to enable the estimation of a variety of forest inventory attributes, including vegetation height, volume, and biomass (Lim et al., 2003; Zhao et al., 2009). We propose that lidar may be employed as a proxy for field plots. These lidar plots can be used to provide a spatially extensive and detailed source of forest attribute information. The concept of lidar plots is portable and may be implemented in any jurisdiction where detailed plot-like information is required over large areas.

In this communication we place the need for lidar plots in context and introduce applicable lidar remote sensing and sampling considerations. To this end, we summarize key national forest monitoring programs in Canada and make recommendations on the use of lidar plots to augment existing protocols. Canadian programs have provincial or state, regional, and international analogues upon which applicable insights are intended. We present considerations for a national lidar survey, including sensor and flight parameters, and make recommendations for a database design to facilitate storage and processing. We provide a description of a case study in Canada's boreal forest where more than 25 000 km of lidar data were collected in the summer of 2010. We conclude with insights gleaned from this case study and recommendations for future activities, improvements, and implementation opportunities.

Background

International context

In response to growing concerns related to climate change, the global community has sought common ground for a series of initiatives such as the United Nations Framework Convention on Climate Change (UNFCCC), the Montreal Process Criteria and Indicators, and support of global reporting by the United Nations Food and Agricultural Organization (FAO). All of these initiatives require timely and accurate information on the status of and changes to forest resources. Additionally, the UNFCCC (in support of the Kyoto Protocol) requires detailed information to support reporting on changes in forest carbon stocks resulting from forest management, afforestation, reforestation, and deforestation. Recently, the UNFCCC agreed to explore an initiative calling for economic incentives to Reduce Emissions from Deforestation and forest Degradation (REDD) in developing countries. A major challenge in the implementation of REDD will be the identification of practical methods to assess carbon emissions resulting from deforestation and degradation in developing countries (Gibbs et al., 2007). A variety of possible approaches exist, including traditional forest inventories, spaceborne optical and microwave remote sensing, and airborne lidar (Gibbs et al., 2007; Asner, 2009). The Remote Sensing Survey of the Food and Agricultural Organization of the United Nations is an example of a sample-based global survey based upon (Landsat) imagery (Potapov et al., 2011) used for determining status and trends in forest cover at a global level.

Spaceborne lidars with the capability to systematically acquire lidar data over large areas and that could support initiatives such as REDD are not common. Despite the successes shown using data from the Geoscience Laser Altimeter System (GLAS) aboard the Ice, Cloud, and land Elevation satellite (ICESat) to characterize regional (Boudreau et al., 2008; Nelson et al., 2009a, 2009b; Dolan et al., 2011) and global (Lefsky, 2010; Simard et al., 2011; Los et al., 2012) forest characteristics, with the cancellation of the Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI) mission (Goetz et al., 2011) there is no planned or forthcoming satellite missions for the collection of lidar data for vegetation characterization. Regardless, scientists are anticipating vegetation applications using ICESat-2 scheduled for launch in mid-2016 (although the laser sensor will differ from the GLAS sensor on ICESat-1) (NASA, 2012). In addition, data collected from a spaceborne system will also have a larger footprint than airborne data (Pang et al., 2011) and, as such, the nature of the information captured is different (see Figure 1 in Wulder et al., 2012; Popescu et al., 2011), and requires calibration (Los et al., 2012). In the absence of space-based lidar, the data collection opportunities arising from airborne lidar provide a practical option for large area representations.

Canadian context

With an area of approximately 400 million ha, forests represent over 53% of Canada's land area (NRCan, 2011). Further, forested ecozones (ecosystems that can support forests, but that also include other land cover types such as lakes and wetlands), represent more than 60% of Canada's landmass (Wulder et al., 2008b). Canada's forests are crucial to the national economy, contributing CAD$23.5 billion to the national balance of trade (NRCan, 2010). Traditionally managed for timber supply, shifting societal values have provided the impetus to adopt a policy of sustainable forest stewardship where forests are also managed for environmental, social, cultural, and other economic considerations (Wulder et al., 2007b; NRCan, 2010). To support forest monitoring and management and to meet national and international reporting responsibilities, the federal government, in co-operation with provincial and territorial agencies, has developed a suite of programs to inventory forests, map land cover, and monitor carbon stocks (Wulder et al., 2004). Together, these programs represent the state-of-the-art in forest assessment at the national level and represent innovation and best practices accepted at the international level (Gillis et al., 2005).

In Canada, the development of remotely sensed "plots" that could serve as a proxy for ground plots in sites that were remote or inaccessible was first explored in the 1920s (Losee, 1942) with a resurgence in research effort in the 1960s (Kippen and Sayn-Wittgenstein, 1964; Sayn-Wittgenstein and Aldred, 1967) and 1970s (Aldred and Hall, 1975; Aldred and Lowe, 1978; Nielsen et al., 1979) and most recently in 2006 (Chapman and Cole, 2006). Spencer and Hall (1988) provided a detailed review of large-scale aerial photographic (LSP) systems developed in Canada. Early trials of these systems were hampered by an inability to rapidly and accurately determine photo scale, resulting in the development of a radar altimeter (Westby, 1967) and tilt-measuring (Nielsen, 1974) system that was tested in both temperate (Aldred and Sayn-Wittgenstein, 1968a) and tropical forest environments (Aldred and Sayn-Wittgenstein, 1968b). Around the same time, a less photogrametrically rigorous LSP system was developed for forest sampling, which consisted of a commercially available radar altimeter and a specially designed intervalometer (Kirby and Hall, 1980). Radar was selected over laser technology for these LSP systems, as lasers were, at the time, markedly more expensive, and had size, power supply, and cooling needs that were difficult to accommodate in a small aircraft (pulsed lasers designed for airborne applications did not emerge until the mid to late 1970s) (Aldred and Bonner, 1985). The utility of the ground profile generated by the radar altimeter and the speed and precision with which it could be produced soon led to a desire for canopy profiles, which were enabled by the use of a double trace radar altimeter (Nielsen and Aldred, 1976; Nielsen and Aldred, 1978). The initial trials of the camera–altimeter system demonstrated the capacity of an airborne lidar-like instrument to measure tree heights and, moreover, highlighted the potential of "photo plots" to be used in a sampling framework to statistically characterize forest resources (Aldred and Lowe, 1978) and to assess forest regeneration (Hall and Aldred, 1992; Pitt et al., 2000). The concept of the photo plot was summarized by Nielsen et al. (1979, p. 1):

> *"The procedure is simple. Aerial photographs are obtained over sample locations at scales that permit accurate species identification and tree measurements (usually crown dimensions and height). The variables measured are entered into*

> *regression models, which provide estimates of stem diameter and tree volume. A statistically sound sampling design ensures that the extrapolation of values to the strata or to the complete inventory area is made without significant bias and that a valid estimate of accuracy can be made.''*

It was not until the mid 1980s that the potential of lidar for forestry was investigated in a Canadian context. Aldred and Bonner (1985) found that stand height (±4.1 m with a 95% confidence level) and crown cover density (within ± one 20% class, 89% of the time) could be measured accurately and that the estimates were ''clearly better than or as good as the readings obtained from photo interpretation'' and furthermore that ''. . . the amount of field work required to support photo interpretation could be greatly reduced and the quality of the work improved because of the more extensive coverage the laser could offer in place of field checking''.

Since these early investigations into laser systems, the confluence of advancements in global positioning systems (GPS), and internal momentum units (IMU) have provided the capacity to accurately record the location and orientation of the aircraft and, subsequently, the location from where a given laser pulse was reflected thereby enabling modern lidar applications. Building on the rapid technological developments of companies such as Optech and Applanix, instrument development and applications capacity progressed through the 2000s. Similar to other jurisdictions (e.g., Scandinavia (Næsset et al., 2004), USA (Evans et al., 2006; Falkowski et al., 2009a; Dubayah and Drake, 2000), among others), Canadian scientists have played an active role in the development of lidar applications for forestry and forest monitoring (e.g., Magnussen and Boudewyn, 1998; Lim et al., 2003; Hopkinson et al., 2008; Wulder et al., 2008a). Due to the nature of the forest stewardship responsibilities in Canada and the large areas involved (Wulder et al., 2007b), a national lidar survey program, such as that in Denmark (Nord-Larsen and Riis-Nielsen, 2010; Nord-Larsen and Schumacher, 2012) has not emerged. It is worth noting that many individual forest management units in Canada are of the same size or larger than the entire national forest area of many other nations (FAO, 2010). Lidar data have been acquired over several managed forest areas in Canada, primarily for individual management units or licence areas (e.g., Woods et al., 2011). As an exception, Alberta has been collecting lidar data over provincial forest lands, resulting in the acquisition and processing of over 28 million ha of lidar data. The provincial coverage is larger than the forested area of Sweden (based upon values reported by the FAO (2010)).

Forest inventory

The Canadian NFI consists of a multiphase plot-based program designed to assess and monitor the state of the nation's forests on a decadal basis (Gillis et al., 2005). In the first sampling phase of the NFI, 1% of the country's landmass is surveyed using a systematic network of approximately 18 500 plot locations, each of which consists of a 2 × 2 km photo plot centered on a 20 × 20 km national grid. The second phase incorporates ground plots established within a 10% random subset of the phase 1 locations. Ground plots are only located within forested or potentially forested locations, and a minimum of 50 plots are established within each ecozone. In the actively managed southern portion of Canada, photo plots are inventoried by manually interpreting 1:20 000 scale aerial photographs. Interpreters first delineate stand boundaries within a photo plot, then use interpretation and allometric models to estimate inventory attributes. In northern areas, where financial and logistical issues limit the acquisition of aerial photography, the EOSD is currently employed to generate land cover and biomass information (Gillis et al., 2005) required for reporting over areas where provincial and territorial inventories are not systematically collected.

Land cover mapping

The EOSD product is a land cover map of the forested ecozones of Canada and represents the most spatially extensive and detailed survey of Canadian forests undertaken to date. The EOSD product was produced using Landsat-7 Enhanced Thematic Mapper Plus (ETM +) data and characterizes forest conditions for the year 2000 (with project and outcomes summarized in Wulder et al., 2008b). In addition to the production of the core land cover product, the EOSD program also included research components related to biomass estimation, forest change monitoring, and the development of automated map production routines (Wulder et al., 2004). The classification system used for EOSD was developed to fit within the hierarchical classification used by the NFI while maintaining a level of detail consistent with what can be derived from Landsat data (Wulder and Nelson, 2003).

Forest carbon accounting

The FCAP is a national initiative under the auspices of the National Forest Carbon Monitoring Accounting and Reporting System (NFCMARS), which was established to meet reporting requirements for the UNFCCC, the Montreal Protocol, and the FAO, among others (for overview see Kurz et al., 2009). To meet these detailed and varied requirements and building upon previous implementations (Kurz et al., 1992; Kurz and Apps, 1999) the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) was developed. Using the ''one inventory plus change'' method, NFCMARS estimates annual changes caused by natural processes and anthropogenic activities. The CBM-CFS3 model requires both a forest and land inventory; data on land use changes, forest management activities, and natural disturbances; and detailed models of growth rates, decomposition, and non-CO_2 emissions. CBM-CFS3 then provides estimates of changes in carbon in 21 pools, which may be aggregated into the five Intergovernmental Panel on Climate Change (IPCC) pools for reporting purposes.

Together, the NFI, EOSD, and the FCAP represent a multifaceted inventorying and reporting framework for monitoring various aspects of Canada's forests (Wulder et al., 2004). While the NFI collects very detailed plot-level data, primarily in managed southern forests, the EOSD extends a limited but important set of attributes to the entire forested area of Canada. The FCAP then uses this information, and other data through partnerships with provincial and territorial agencies, to model changes in carbon pools to meet a variety of national and international reporting obligations. All three of these programs currently use plot level forest information in some manner, and therefore each are a potential end user of lidar-plots.

Forest plots

Forest inventories are designed to provide information on the extent, quantity, and condition of forests (Penman et al., 2003) and are typically completed through some form of sampling, as a complete census is often impossible, unfeasible, too costly, and time consuming (Freese, 1962). Sampling in forest inventory was common a century before the use of representative samples was recommended by Norwegian statistician A.N. Kiaer in 1899 (Seng, 1951; Kangas and Maltamo, 2006). Although line and point samples were favoured in the past (Frayer and Furnival, 1999), samples today primarily take the form of plots, with many nations having plot-based national forest inventory programs (Tomppo et al., 2010). Plots provide a tested and trusted means of gathering information on forest structure and condition. By the 1950s, sampling systems based on aerial photo plots had been implemented in the United States (Bickford, 1952), and the current U.S. and Canadian NFI programs continue to use photo plots for phase 1 stratification purposes (Bechtold and Patterson, 2005; Gillis et al., 2005). The improved efficiency of sampling programs resulting from the use of ground and air photo plots has prompted investigations into the use of samples of lidar as "lidar plots" (Parker and Evans, 2004; Andersen et al., 2009; Bater et al., 2011; Wulder et al., 2012). Inventory plots of any origin, be they derived from direct field measurement, photos, or lidar, will continue to play an important role in forest inventory and management.

Lidar and forest attributes

Lidar data has a demonstrated capacity to support the estimation of a variety of attributes of interest to forest monitoring and assessment programs, including those related to vegetation height, stand and crown structure, and volume and biomass (Lim et al., 2003, Wulder et al., 2008a). Operational applications of lidar in forest inventory and assessment are increasingly mature. Herein we summarize exemplar publications related to forest structure (**Table 1**)

Table 1. Use of airborne scanning lidar for the assessment of forest structure.

Variables	Level of analysis	Laser pulse distance or density	Accuracy/ goodness of fit	Error	Source
Stand height	Plot	11 canopy hits per 100 m^2	$R = 0.8$	Within 6%, mean of 3%	(Magnussen and Boudewyn, 1998)
	Plot	Point distance =	R^2 =	Standard deviations =	(Næsset, 2002)
Mean height		0.9 m	82–95%	0.61–1.17 m	
Dominant height			74–93%	0.70–1.33 m	
	Plot	Point distance =	R^2 =	n/a	(Riano et al., 2004a)
Crown bulk density		1.73 m	0.80		
Crown volume			0.92		
Foliage biomass			0.84		
	Crown	10 points/m^2	R^2 =	RMSE =	(Morsdorf et al., 2004)
Height			0.92	0.61 m	
Crown diameter			0.20	0.47 m	
	Plot	3.5 points/m^2	R^2 =	n/a	(Andersen et al., 2005)
Canopy fuel weight			0.86		
Canopy base height			0.77		
Canopy height			0.98		
	Crown	5 points/m^2	n/a	RMSE =	(Solberg et al., 2006)
Crown height,				0.8–3.3 m	
Crown base height				2.7–3.7 m	
Crown diameter				1.1–2.1 m	
Height	Crown	6 points/m^2	n/a	Mean ± std = –0.73 ± 0.43 m	(Andersen et al., 2006)
Canopy height	Plot	Point distance 0.6–2.0 m	$R^2 = 0.95$	RMSE = 1.8 m	(Hopkinson et al., 2006)
Wildlife tree class	Plot	0.7 points/m^2	$R = 0.61$–0.90	RMSE = 6.0–16.8%	(Bater et al., 2009)
Forest successional stage	Plot	0.26 points/m^2	Class accuracies 73–100%	n/a	(Falkowski et al., 2009a)

and volume and biomass (**Table 2**) that are commonly estimated using scanning airborne lidar that can be, and have been, incorporated into operational large-area sampling programs. Lidar is particularly well suited to the estimation of height (Andersen et al., 2006; Hopkinson et al., 2006), and volume and biomass (Maclean and Krabill, 1986; Nelson et al., 2003; Popescu, 2007; Næsset and Gobakken, 2008). Other attributes, such as species (Moffiet et al., 2005; Ørka et al., 2009), standing dead wood, and coarse woody debris (Seielstad and Queen, 2003; Pesonen et al., 2008; Bater et al., 2009; Martinuzzi et al., 2009) are areas of active research, but are not likely to be estimated with confidence on an operational basis using lidar.

Lidar as a large-area sampling tool

The application of scanning lidar as a sampling tool for large-area monitoring is an active and varied research topic (e.g., Hudak et al., 2002; Andersen et al., 2009; Armston et al., 2009; Asner et al., 2010; Moffiet et al., 2010; Chen and Hay, 2011; Hall et al., 2011; Hopkinson et al., 2011). Different remote sensing technologies have been employed as sampling tools for national forest inventories. The Canadian NFI, for example, relies heavily on the use of aerial photography (Gillis et al., 2005), and the recent development of programs such as EcoMonitor (Falkowski et al., 2009b) provides an operational example whereby very high spatial resolution (VHSR) satellite data are being used to augment forest inventory estimates in remote northern areas. Less common operationally is the use of lidar samples to support forest inventories.

Wulder et al. (2012) provided an extensive review of the use of lidar as a sampling tool for large-area estimation of forest vertical structure, highlighting specific theoretical and statistical considerations and providing recommendations for best practices. Although research has primarily focused on the use of airborne scanning lasers, airborne profiling and full waveform lasers, as well as spaceborne lasers, have all been used in a sampling mode to support the characterization of a range of forest attributes, including forest structure, volume, biomass, carbon stocks, and habitat. Several recent examples of the use of lidar samples in support of forest inventory are provided, most notably, in Hedmark, Norway (Næsset et al., 2009; Gregoire et al., 2011; Ståhl et al., 2011; Gobakken et al., in press; Nelson et al., in press), Quebec, Canada (Boudreau et al., 2008; Nelson et al., 2009a), New Zealand (Beets et al., 2010, Stephens et al., 2012), and Alaska (Andersen et al., 2009, 2011).

A recent example of lidar samples in support of forest inventory not included in the review by Wulder et al. (2012) is that of Chen et al. (2012), which introduced a Geographic Object-Based Image Analysis (GEOBIA) framework to estimate canopy height, aboveground biomass (AGB), and volume. The authors refined a lidar transect selection algorithm (Chen and Hay, 2011) and applied it to a 16 330 ha mixed forest site in Quebec, Canada. The lidar transect selection was determined by sample size, orientation, location, and representative canopy height sampling. VHSR imagery (QuickBird) and machine learning algorithms were then used to generalize the sampled lidar measurements to the entire study site. Estimates generated from a lidar sample representing only 7.6% of the total study area, were strongly correlated to estimates using wall-to-wall lidar coverage for canopy height ($R = 0.85$; root mean squared error (RMSE) = 3.37 m), AGB ($R = 0.85$; RMSE = 39.47 Mg/ha), and volume ($R = 0.85$; RMSE = 52.59 m^3/ha).

Beyond forest inventory, samples of lidar can also support other applications such as estimating the volume of pine lost to a mountain pine beetle infestation in British Columbia (Bater et al., 2010) or assessing post-fire canopy recovery in the unmanaged area of Canada's boreal forest (Magnussen and Wulder, 2012). Bater et al. (2010) proposed a method whereby lidar and digital aerial imagery were used in a sampling approach to estimate pine volume losses from mountain pine beetle at the plot level. Fifty-five 0.25 ha photo plots were established and mean plot-level dominant stand heights were derived from lidar data. Tree species, health status, and stem diameter and density were manually interpreted from the aerial imagery, and these attributes were then combined with the lidar-derived height information

Table 2. Use of airborne scanning lidar for the assessment of volume and biomass.

Variables	Level of analysis	Laser pulse distance or density	Accuracy/ goodness of fit	Error	Source
Volume	Plot	Point distance = 0.9 m	$R^2 = 80–93\%$	18.3–31.9 m^3/ha	(Næsset, 2002)
Basal area Stem volume	Plot	Point distance = 0.5–0.8 m	$R = 0.94$ 0.97	RMSE = 2.7 m^2/ha (10%) 31 m^3/ha (11%)	(Holmgren, 2004)
Timber volume	Crown	10 points/m^2	n/a	RMSE = 16–25% bias = 8.2–24.3%	(Maltamo et al., 2004)
Biomass Volume	Plot	Point distance = 0.7 m	$R^2 = 0.32–0.82$ 0.39–0.83	RMSE = 29–44 Mg/ha 48–53 m^3/ha	(Popescu et al., 2004)
Dbh Biomass	Crown	2.6 points/m^2	$R^2 = 0.87$ 0.88	RMSE = 18% 47%	(Popescu, 2007)
Aboveground biomass	Plot	4 to > 4 points/m^2	$R^2 = 0.67–0.88$	n/a	(Li et al., 2008)
Aboveground biomass Belowground biomass	Plot	0.7–1.2 points/m^2	$R^2 = 88\%$ 85%	RMSE = 0.25 Mg/ha 0.27 Mg/ha	(Næsset and Gobakken, 2008)

using species-specific equations to estimate the volume of pine killed within each of the sampled plots. The plot-level procedures for producing estimates of infestation impact were developed to form the basis for a large-area, sample-based monitoring program. Magnussen and Wulder (2012) used samples of lidar collected coincident with 163 historic fires of known start date and duration located across Canada's unmanaged boreal forest to determine whether the forest canopy was completely or partially restored to these burned areas post-fire. Of the 153 fires that predated the acquisition of the lidar data by more than 5 years, 89% had complete or partial post-fire canopy replacement.

Lidar plots for large-area sampling

A lidar plot may be thought of as a defined area, analogous to a fixed radius (or size) ground or photo plot, from which height and in some cases backscatter intensity-related metrics are summarized using a variety of statistics. Critically, where the cost of establishing ground plots in isolated forest areas may be prohibitive, lidar plots could be employed to capture a range of variability representative of large areas (Andersen et al., 2009). Examples of plot-level vegetation metrics calculated from lidar returns include percentiles (Magnussen and Boudewyn 1998; Næsset and Økland 2002; Riano et al., 2004a; Gobakken and Næsset 2005): mean, maximum, standard deviation, skewness, kurtosis, and coefficients of variation of vegetation return heights (Næsset and Økland 2002; Andersen et al., 2005; Hopkinson et al., 2006); and estimates of vegetation cover based on ratios of first returns above a given height to the total number of first returns (e.g., Riano et al., 2004b; Goodwin et al., 2006) or the echo classification combined with the pulse return intensity distribution (Hopkinson and Chasmer, 2009).

Sample design

The choice of sample design is governed primarily by the information needs of the particular application in question, but also by the resources available to conduct the survey, the type of lidar data to be acquired, and statistical considerations such as the desired level of precision (Wulder et al., 2012). At present, lidar-derived estimates of forest attributes rely on the development of statistical models relating spatially coincident plot-level lidar and ground data. Because the relationships between lidar metrics and many forest attributes are highly correlated, lidar can be employed as an auxiliary variable to reduce the number of field plots required and (or) improve the precision of forest inventory estimates. Thus, a large-area lidar-based inventory would likely consist of a design-based multistage (Næsset, 2002; Andersen et al., 2009; Gregoire et al., 2011) or multiphase design (Næsset, 2004b; Nelson et al., 2004; Parker and Evans, 2004; 2007; Evans et al., 2006). Several previous studies into the development of sampling frameworks for airborne lidar data have employed systematic lines that were also stratified according to land cover, forest type, or age (Andersen et al., 2009; Nelson et al., 2004; Parker and Evans, 2007).

In Canada, the existing NFI sampling grid provides an ideal framework on which a lidar sampling program could be established (Gregoire et al., 2011). Although collecting lidar data at each of the approximately 18 500 NFI photo plot locations is neither feasible nor practical, collecting data over strata defined by ecological regions[5] could reduce costs, while providing sufficient information for large-area inventory purposes. Furthermore, the use of the existing NFI framework would simplify the incorporation of lidar-derived metrics into the national forest monitoring system. Following such an approach, lidar transects would be designed to coincide with the locations of existing NFI sampling grid lines: sampling strategies could include sampling from randomly selected grid lines; systematic sampling of north–south and (or) east–west oriented grid lines; a hybrid of the two approaches, where both systematically-spaced and randomly selected grid lines are surveyed to minimize sample bias; or the selection of grid lines based on probability proportional to size (or length) (**Figure 1**). Regardless of how flight lines are selected, lidar plots could further be sub-sampled from within a swath to reduce processing cost and effort. Other nations have similar systematic NFI sampling grids that could likewise be used as the basis for a lidar sampling program (Lawrence et al., 2010).

Flight and sensor parameters

The selection of flight and sensor parameters is a critical consideration when designing an airborne lidar survey, as together they directly impact return density, swath width, footprint diameter, and lidar-based height metrics, which in turn influence the bias and accuracy of derived forest biophysical variables. Flight and sensor parameters typically adjusted for a given survey include: flying altitude, pulse repetition frequency (PRF), and scan angle. For example, a survey acquired at an altitude of 1200 m, with a PRF of 70 kHz (70 000 pulses per second) and a scan angle of ± 15 degrees, will have a point density of approximately 2.8 points/m^2 and a swath width of 630 m. If the PRF is reduced from 70 kHz to 50 kHz, the swath width will be maintained, but the point density will be reduced to approximately 2.0 points/m^2. Increasing the altitude to 1800 m will have a similar effect, reducing point density to approximately 2.0 points/m^2, while increasing the swath width and pulse footprint.

Baltsavias (1999) provided a suite of equations describing how lidar acquisition parameters control point density, swath width, and footprint size. Bater et al. (2011) established the stability of lidar metrics when flight and sensor

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[5] An ecological unit characterized by distinctive regional ecological factors, including climate, physiography, vegetation, soil, water, and fauna (Marshall et al., 1999).

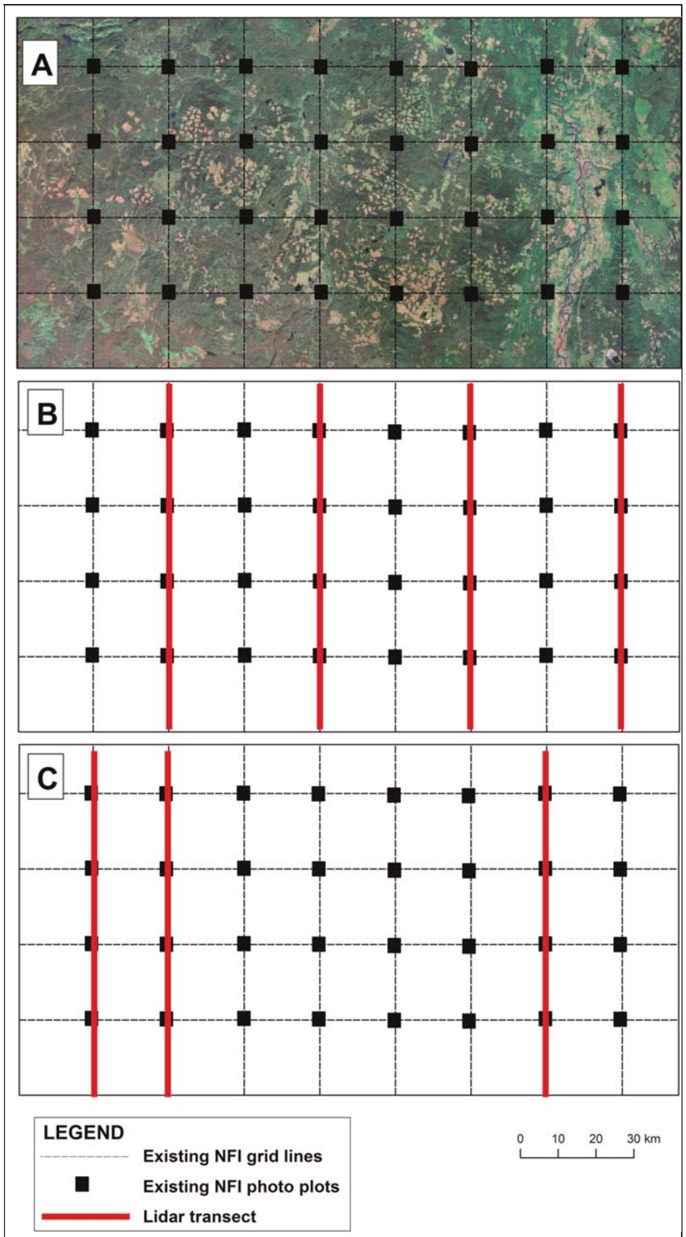

Figure 1. Some possible large-area sampling scenarios using the existing NFI sampling grid (A) include: systematic sampling of north/south oriented NFI grid lines (B), random sampling of NFI grid lines (C), or a hybrid approach combining both systematic and random sampling (not shown). Available land cover data could also be used as a stratification layer.

parameters are maintained, while Næsset (2004a; 2005, 2009), Chasmer et al. (2006), Goodwin et al. (2006), and Hopkinson (2007), demonstrated how variation in these parameters may influence a variety of forest attribute estimates. Reutebuch and McGaughey (2008) suggested a set of minimum recommended lidar specifications for forestry applications (**Table 3**). These parameters include: laser beam divergence, scan angle, pulse repetition frequency, pulse density per square metre, returns per pulse, swath overlap, and absolute lidar measurement accuracy. These specifications will vary depending on whether the information need is for stands or individual trees, with pulse repetition frequency remaining the chief consideration.

Acquisition considerations

Although it is desirable to establish an optimal survey configuration based on a fixed set of sensor and flight parameters, considerations must be made for unforeseen circumstances that require deviations from this optimal specification. Factors such as poor weather conditions, cloud, smoke from wildfires, extreme topography, airspace restrictions, and so on may necessitate spontaneous alterations to acquisition parameters. In such cases, knowledge of an acceptable range of deviation from the optimum, in terms of the impact to point density and swath width, is desirable to ensure the utility of the data for its intended applications. Thus, the minimum specifications listed in **Table 3** provide a frame of reference against which alterations to acquisition parameters may be assessed.

Mass data processing

Large-area mapping (e.g., at the national level) would necessitate the collection of a large number of lidar plots. Many of the current commercial lidar systems typically capture more than two returns for each emitted pulse (i.e., first and last returns), for example, the ALTM Orion system provides up to 4 range measurements for each pulse (Optech, 2012). Given that lidar characterization of forests requires relatively high point densities (e.g., >1 point/m^2), a major issue then becomes how to handle and process hundreds of millions of lidar points: custom software may be required to manage data pre-processing operations for these large point file datasets.

Database development

Critical to the long-term success of a large-area lidar survey is the dissemination of collected and (or) processed data to a wide variety of users, including various government bodies and academic institutions. The inherent complexity of lidar data (i.e., three-dimensional point clouds stored in binary format) must be reduced so that it is provided in a useable format; that is, data must be made transparent to users and be readily accessible, hierarchical, and spatially explicit.

Software products such as PostgreSQL[6] provide a suitable method for dissemination. PostgreSQL is an open-source relational database that may be accessed from a number of programming languages and closely follows industry standards for query languages. A database might contain a suite of plot-level lidar-derived metrics and forest inventory attributes and an example of such a database is provided

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[6] PostgreSQL website: http://www.postgresql.org/

Table 3. A summary of minimum lidar acquisition parameters for forestry applications.*

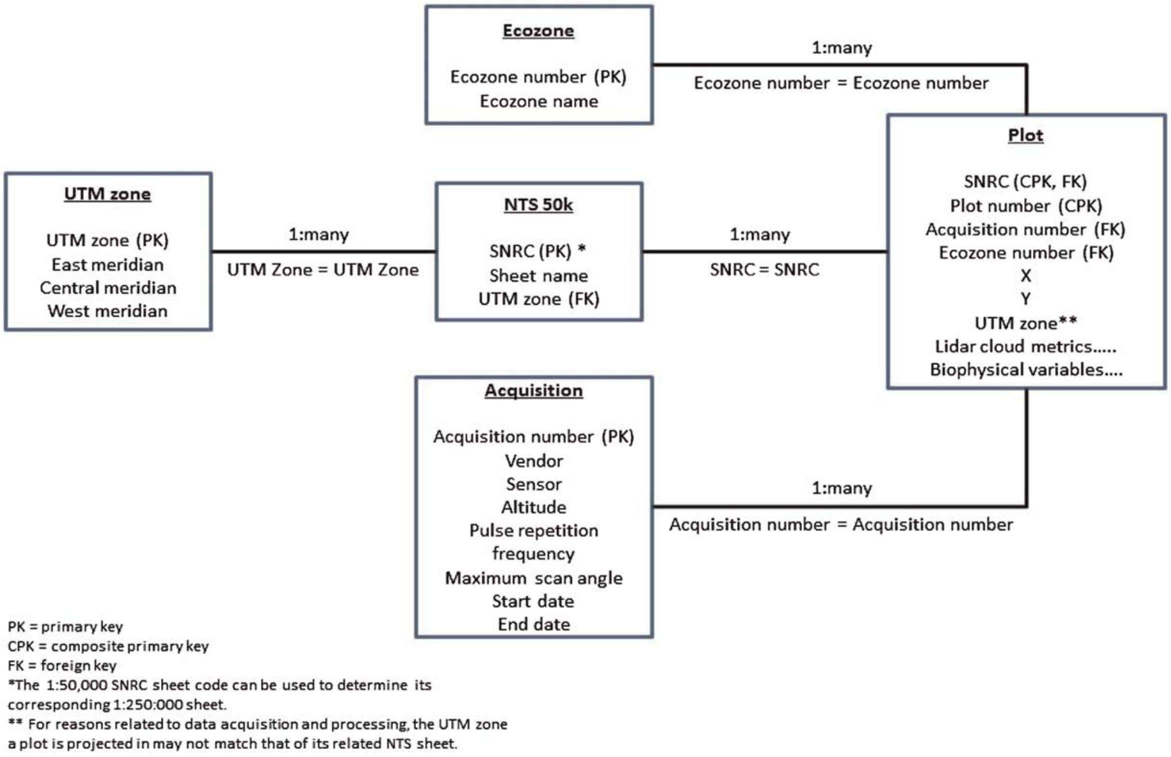
Acquisition parameter	Recommended specification for forestry applications
Laser beam divergence	Narrow (e.g., 0.3 mRad; with "narrow" typically considered as ranging from 0.1 to 0.6 mRad).
Scan angle	±15 degrees (forest density can be used to guide scan angle, with more open canopies allowing for a greater scan angle).
Pulse repetition frequency	30 kHz to > 100 kHz (noting that newer systems offer greater PRFs, with project aims guiding the selection of PRF).
Pulse density per square metre	As a heuristic, consider a minimum of 1 for stand level canopy models and medium resolution DEMs (2 m). If interested in individual tree-canopy measures, greater pulse rates are required (i.e., > 4) with the size of the crown a primary consideration. Production of a high resolution DEM under a dense canopy also indicates a need for a greater pulse density (i.e., > 4).
Returns per pulse	Minimum 2 for canopy and ground-surface measurements.
Swath overlap	> 50% sidelap on adjoining swaths. (Note that this is not a relevant consideration for transect sampling).

*Adapted from Reutebuch and McGaughey (2008).

in **Figure 2**. For convenient indexing, each lidar plot could be related to a topographic map sheet. Furthermore, each plot could also be related back to an ecozone and its survey acquisition information. The final design would be implemented in such a way that users from diverse backgrounds, with some basic experience using relational databases, could access and apply the information with relative ease.

Case study: Boreal Canada

To support improved monitoring of Canada's northern forests and investigate the capacity to characterize a region beset by a paucity of information, the Canadian Forest Service has undertaken a project to collect samples of lidar data across the boreal forest. Priority areas included ecoregions that are greater than 85% boreal, greater than 50% forested, and less than 75% managed forest. Over a period of 67 days from June to August, 2010, 34 individual survey flights were made traversing 13 UTM zones, from Newfoundland (56° W, UTM zone 21) in the east to the Yukon (138° W, UTM zone 8) in the west (**Figure 3**). Latitudinally, the flights extended from 43° to 65° N. Survey flights were made between airports with suitable runways, fuel availability, and maintenance facilities, and they ranged from one to five hours in duration. While exceeded by the total flying distance, the length of the transects is greater than 25 000 km, with an average transect length of 700 km.



PK = primary key
CPK = composite primary key
FK = foreign key
*The 1:50,000 SNRC sheet code can be used to determine its corresponding 1:250:000 sheet.
** For reasons related to data acquisition and processing, the UTM zone a plot is projected in may not match that of its related NTS sheet.

Figure 2. An entity relationship diagram showing examples of tables and columns that may be present in a relational database intended for disseminating data collected by a large-area lidar-based inventory.

Figure 3. Map displaying the 34 flight lines acquired in the summer of 2010 that together make up the boreal case study lidar transect dataset.

Data were collected using a discrete return sensor (Optech ALTM 3100), which is capable of four measured returns per pulse. The desired survey specifications included a flying height of 1200 m above ground level (agl), a 70 kHz PRF, and a scan angle of ±15°, resulting in a nominal pulse density of approximately 2.8 returns/m^2. Due to adverse weather, extreme terrain, excessive smoke from wildfires, and restricted airspace, deviations from this optimal plan were necessary for 24 of the 34 flights. For example, while all 34 flights were conducted between altitudes of 450 to 1900 m agl, 11 flights were conducted at altitudes $<$ 900 m agl, and three flights were conducted at altitudes $>$ 1500 m agl. The scan angle was kept fixed at 915° for all but four of the flights and PRF kept at 70 kHz for all but seven. Low cloud ceilings forced a scan widening of up to 20°, while extreme terrain dictated a reduction in PRF to 50 kHz. In cases where ceilings or visibility reduced the flying height, data density was minimally impacted and likely increased despite adjusted scan angles. Where terrain necessitated a reduction in PRF, data density was decreased.

Deliverables from the survey included global positioning log files mapping the flight lines and LAS binary files containing classified (ground and nonground) lidar point clouds. Post-processing involved the computation of the single best-estimated trajectory (sbet), containing both position (GPS) and orientation (IMU) information. The laser range data was then integrated with the sbet, resulting in the raw output file (in LAS 1.0 format). The ground returns were then classified from the point cloud using a variant of the algorithm developed by Axelsson (2000). Many of the LAS files acquired for this study were too large ($>$ 30 GB) to be handled in most software environments, necessitating the development of a customized software tool to clean the data, classify the ground points, and partition the LAS files into manageable sub-units containing a maximum of 20 million data points each.

Subsequent processing involved the establishment of plot locations and the derivation of lidar plot attributes. A 25 × 25 m tessellation was generated with the approximately 400 m wide lidar swath, with each cell treated as an individual lidar plot. Plot-level metrics were calculated from the classified LAS files using FUSION (McGaughey, 2010), a publicly available software tool developed by the U.S. Forest Service (**Table 4**). The resulting plot-level metrics were then stored in a relational database (developed in PostgreSQL). There were more than 17 million lidar plots and almost five billion first returns with a height greater than 2 m, representing an area of approximately 1.2 million ha.

To estimate forest inventory attributes for the lidar plots, a dataset of spatially coincident lidar and field data from across a range of boreal ecozones was compiled from 201 plot locations in Québec, Ontario, and the Northwest Territories. Best subsets linear regression was then used to predict plot-level attributes (dependent variables) using lidar metrics as independent variables. The forest attributes estimated for each plot included: mean, dominant, and Lorey's height; gross stem volume; and total aboveground biomass. The final regression models used for estimation (**Table 5**) explained between 64% and 84% of the variance in the forest attributes (**Table 6**). The median values for the modeled attributes are summarized by ecozone in **Table 7**. In **Figure 4**, we present examples of the metrics and

Table 4. List of plot metrics produced using FUSION (McGaughey, 2010) and attributes modeled using a sample of field measures.

Source	Metric
First returns above 2 m height threshold	Total number of returns above minimum height
	Count of returns by return number (support for up to 9 discrete returns)
	Minimum
	Maximum
	Mean
	Median (output as 50th percentile)
	Standard deviation
	Variance
	Coefficient of variation
	Interquartile distance
	Skewness
	Kurtosis
	AAD (Average Absolute Deviation)
	L-moments (L1, L2, L3, L4)
	L-moment skewness
	L-moment kurtosis
	Percentile values (1st, 5th, 10th, 20th, 25th, 30th, 40th, 50th, 60th, 70th, 75th, 80th, 90th, 95th, 99th percentiles)
	Percentage of first returns above a specified height (canopy cover estimate)
	Percentage of first returns above the mean height/elevation
	Percentage of first returns above the mode height/elevation
	Percentage of all returns above a specified height
	Percentage of all returns above the mean height/elevation
	Percentage of all returns above the mode height/elevation
	Number of returns above a specified height/total first returns * 100
	Number of returns above the mean height/total first returns * 100
All returns, including ground and nonground	Total number of returns
	Mean height (or elevation)
	Standard deviation of height (or elevation)
	75th percentile value
	Volume under upper canopy surface
Modeled attributes ($n = 201$)	Mean tree height
	Dominant tree height
	Lorey's mean tree height
	Basal area
	Gross stem volume
	Total biomass

Table 5. Multiple linear regression models for the field-measured inventory attributes (dependent variables) and lidar canopy height and cover metrics (predictors).*

Dependent variable	Equation
Mean tree height	$\exp(1.5856 + (0.4049 \times \ln(\mathrm{Lh}_{\mathrm{mean}})) + (0.0646 \times \ln(\mathrm{Lh}_{\mathrm{stdev}}))) \times 1.0042$
Dominant tree height	$\exp(0.7247 + (0.7222 \times \ln(\mathrm{Lh}_{\mathrm{p95}})) + (0.0548 \times \ln(\mathrm{CC}_{\mathrm{2m}}))) \times 1.0036$
Lorey's mean tree height	$\exp(0.7341 + (0.7215 \times \ln(\mathrm{Lh}_{\mathrm{p95}}))) \times 1.0037$
Basal area	$(\exp(-3.5248 + (1.1240 \times \ln(\mathrm{Lh}_{\mathrm{mean}})) + (0.1757 \times \ln(\mathrm{Lh}_{\mathrm{cv}})) + (0.2512 \times \ln(\mathrm{CC}_{\mathrm{2m}}))) \times 1.0415) \times (25^2/20^2)$
Gross stem volume	$(\exp(-2.79766 + (1.411911 \times \ln(\mathrm{Lh}_{\mathrm{mean}})) + (0.31286 \times \ln(\mathrm{Lh}_{\mathrm{cv}})) + (0.28910 \times \ln(\mathrm{CC}_{\mathrm{2m}}))) \times 1.0401) \times (25^2/20^2)$
Total aboveground biomass	$(\exp(4.1060 + (1.6788 \times \ln(\mathrm{Lh}_{\mathrm{mean}})) + (0.2158 \times \ln(\mathrm{Lh}_{\mathrm{cv}})) + (0.2726 \times \ln(\mathrm{CC}_{\mathrm{2m}}))) \times 1.0376) \times (25^2/20^2)$

*All lidar metrics were calculated using first returns above a two metre height threshold.

Note: $\mathrm{Lh}_{\mathrm{mean}}$, Mean first return height; $\mathrm{Lh}_{\mathrm{stdev}}$, standard deviation of the first return heights; $\mathrm{Lh}_{\mathrm{cv}}$, coefficient of variation of the first return heights; $\mathrm{Lh}_{\mathrm{p95}}$, 95th percentile of the first return heights; $\mathrm{CC}_{\mathrm{2m}}$, percentage of first returns above 2 m; $\mathrm{CC}_{\mathrm{mean}}$, percentage of first returns above the first return mean height.

Table 6. Summary statistics for the multiple linear regression models for the field-measured inventory attributes (dependent variables) and lidar canopy height and cover metrics (predictors).

Dependent variable	No. of plots	Adjusted R^2	Bias	RMSE
Mean tree height (m)	201	0.74	0.007	1.33
Dominant tree height (m)	201	0.84	0.008	1.63
Lorey's mean tree height (m)	201	0.83	0.009	1.34
Basal area (m^2)	199	0.64	0.014	0.30
Gross stem volume (m^3)	198	0.80	0.140	2.74
Total biomass (kg)	198	0.76	56.80	1353.21

Table 7. Median plot-level values for forest attributes summarized by ecozone.*

Ecozone	Number of lidar plots	Mean tree height (m)	Dominant tree height (m)	Gross stem volume (m^3)	Total aboveground biomass (kg)	Total aboveground biomass (tonnes/ha)
Atlantic Maritime	45,130	12.2	16.4	4.62	8,238	132
Boreal Cordillera	175,050	10.8	14.1	2.76	4,526	72
Boreal Plains	29,047	9.4	10.9	1.66	2,597	42
Boreal Shield	398,182	9.6	11.1	1.68	2,637	42
Hudson Plains	80,971	7.8	6.9	0.51	767	12
Taiga Plains	151,449	9.1	10.1	1.28	1,961	31
Taiga Shield	118,839	9.0	9.8	1.20	1,844	30
All Groups	1,011,635	9.4	10.9	1.58	2,460	39

*Data are based on a systematic sample of approximately 5% of the lidar plots database.

attributes for a section of a single transect. Recall the distinction between metrics, which are generated directly from the lidar data, and attributes, which are estimates based upon empirical relationships between metrics and co-located field measurements. A canopy height model can be generated for the lidar plot supporting the generation of other plot-level information (e.g., identification of individual tree crowns) and enabling the characterization of within plot variability in tree heights (**Figure 5**).

This case study highlights three important stages that must be considered for a project of this scope. First is the logistical challenge of surveying a large, extremely isolated area. Two months were required to fly the transects, and maintaining the original optimal survey configuration was often not possible given terrain or environmental conditions. Some concessions were also made during flight to accommodate the conditions present during a given transect acquisition. For example, flying distances were not as far as might be expected to ensure that sufficient fuel was available to enable recovery in the event of an emergency (e.g., closure of planned destination), not just to accomplish a point-to-point distance. Additionally, practical considerations also limited which airports could be used. Some airports are winter only access, others are private or have no fuel sales (requiring precaching of fuel), or had runway materials not conducive to landing an aircraft with a photo port and sensitive equipment. Gravel runways can harm the photo port with errant rocks or are sufficiently rough that the equipment can be damaged. Smoke from wildfires also resulted in changes to planned flight lines. The broad thematic specification of the survey enabled flexibility during acquisition to alter flight lines as necessary. With a goal to collect as much data as possible, the flexibility enabled data to be continuously collected (via alternate flight lines), rather than having to wait for optimal conditions. Second, the large amount of data collected (approximately 18.5 billion lidar returns in total) necessitated the development of numerous custom software tools for the automation of ground–nonground filtering, plot location determination, and extraction of auxiliary information. Third, significant effort was required to collect coincident plot-level ground and lidar data from a range of forest conditions for model development for additional forest attributes.

Conclusion

Previous research efforts have emphasized wall-to-wall lidar-based forest inventories, with less consideration given to sample-based support of forest monitoring programs over large areas. Many forested areas, especially in the boreal, are remote, and as a result, the establishment of traditional ground- and aerial photo-based plots is logistically and economically challenging. For example, the installation of a single ground plot in a remote location can cost several thousand dollars. These high costs per plot may lead to the establishment of fewer plots or to the establishment of plots in biased locations (such as only near roads or airports). This compromise of sampling intensity and integrity can reduce the reliability of the statistics generated. In the context of a sample-based lidar survey, ground plots remain necessary for calibration purposes to improve the quality and reliability of the metrics developed from the lidar data. We propose that calibrated lidar measures are sufficiently

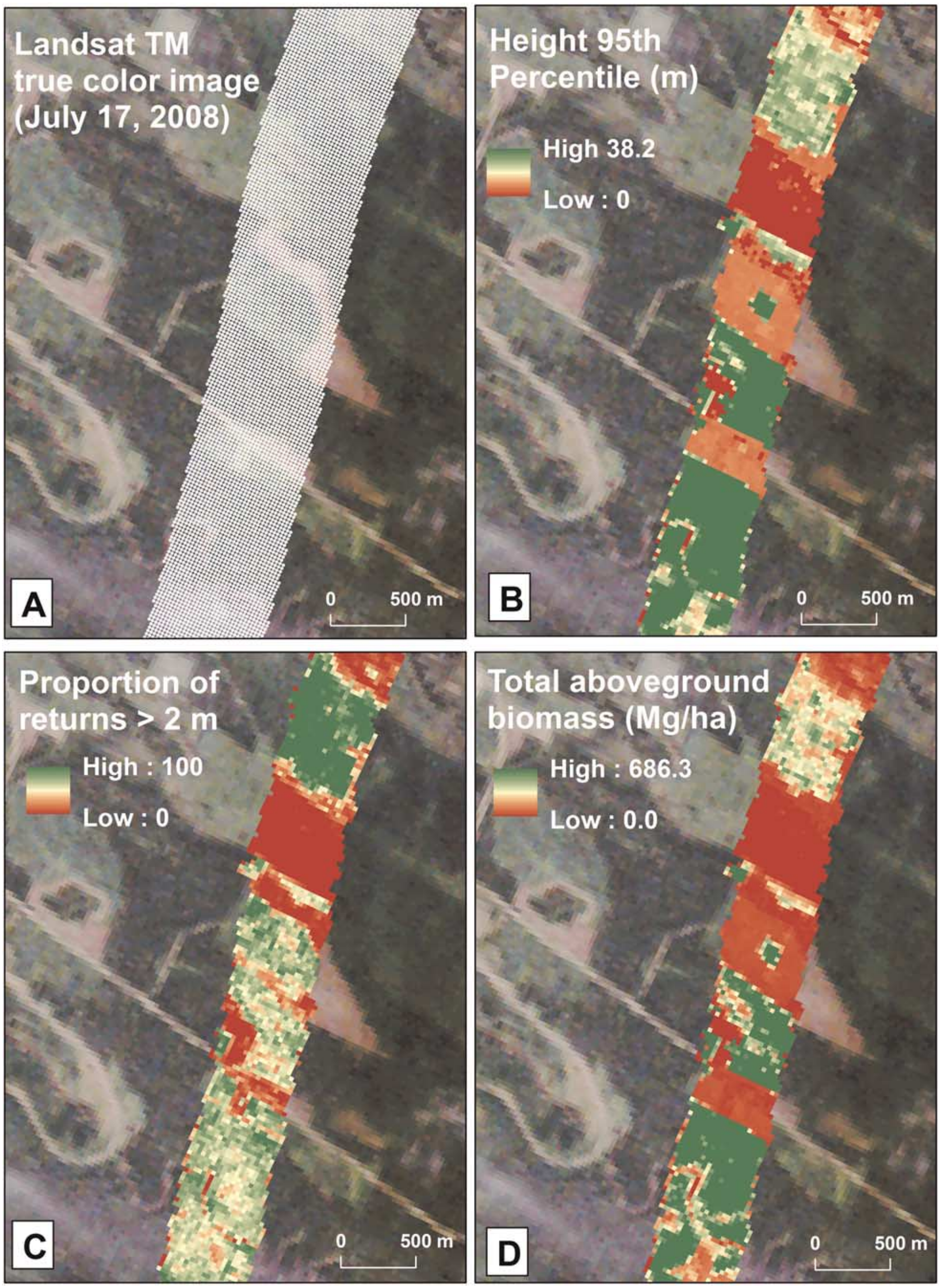


Figure 4. Landsat image (2008, path 50, row 19) located in northeast British Columbia as a backdrop to illustrate the mosaic of forest conditions and select information derived from the lidar plots. In panel (A) the transect location is noted. Each 25 × 25 m lidar plot is populated with a number of metrics and attributes, with examples (B) 95 percentile of height (metric); (C) proportion of hits greater than 2 m (metric); and (D) biomass (attribute).

reliable to augment the forest-plot needs of large-area monitoring programs. Lidar-plots can serve as calibration and validation data for modeling activities, or, given sufficient design forethought, can support forest resource reporting. The actual purpose of the lidar survey will dictate a number of planning considerations. A probability sample and generation of population level statistics on forest resources will require greater attention to transect location and coverage than will surveys intended to capture local conditions in a less formalized manner. Nonprobability based collections of transects serve a valuable role in capturing vertical forest structural conditions. These opportunistic surveys produce plot-like data, which once calibrated, can be used to serve information needs typically addressed with field data. The use of lidar plots can augment Canadian and international forest monitoring and assessment programs by providing additional information that may be brought into existing sampling frameworks.

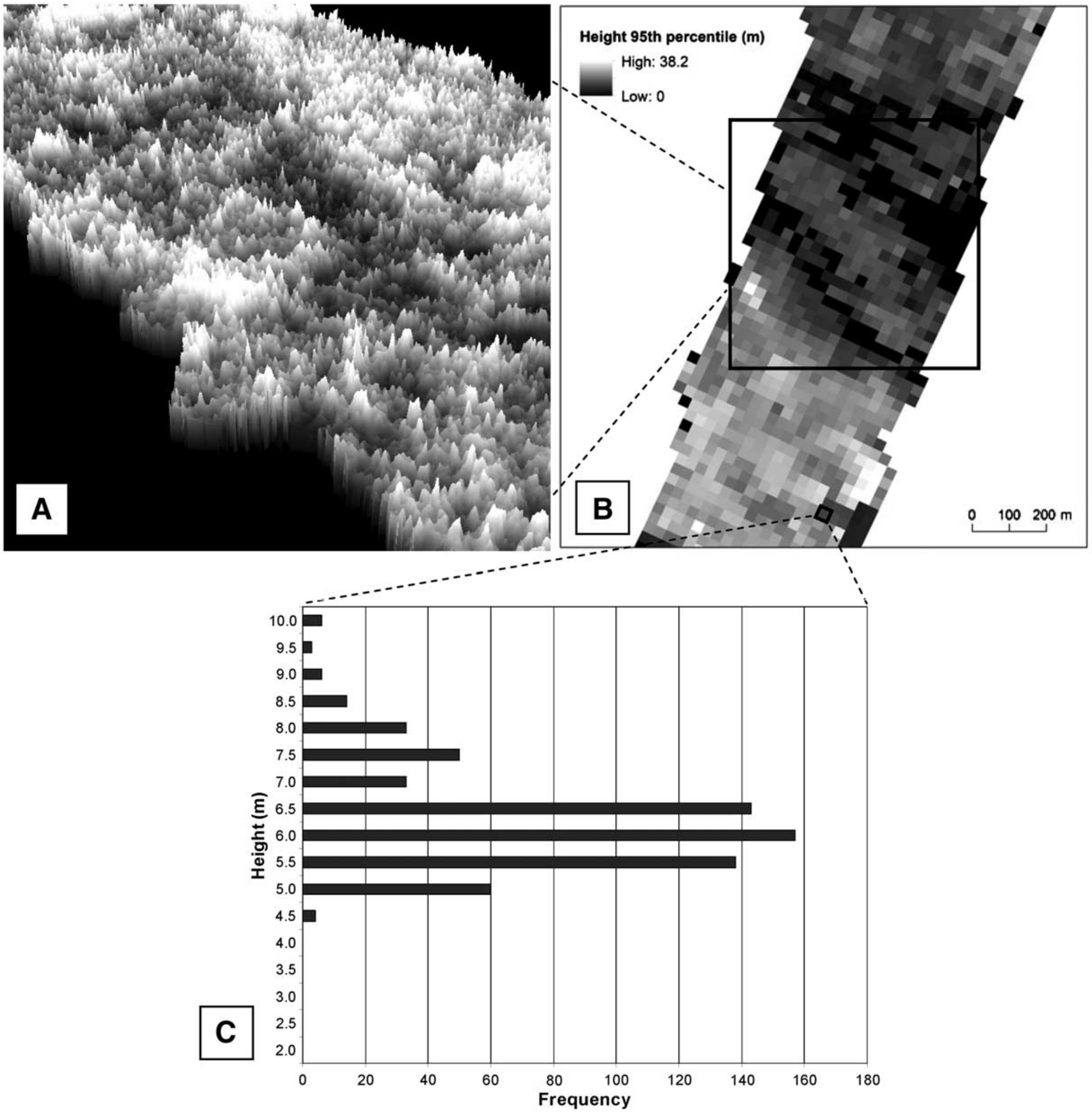


Figure 5. Lidar provided detailed plot-level information: (A) A three-dimensional rendition of a portion of a lidar transect acquired for the boreal Canada case study, generated from a 1 m CHM (Canopy Height Model); (B) A grid-based representation of heights: 95^{th} percentile of lidar heights generated from each 25 × 25 m lidar plot along a lidar transect. (C) Within plot-variability: tree height distributions within each plot can be generated from the 1 m CHM and enable the development of a suite of distributional statistics.

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