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Status and prospects for LiDAR remote sensing of forested ecosystems

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Abstract. The science associated with the use of airborne and satellite Light Detection and Ranging (LiDAR) to remotely sense forest structure has rapidly progressed over the past decade. LiDAR has evolved from being a poorly understood, potentially useful tool to an operational technology in a little over a decade, and these instruments have become a major success story in terms of their application to the measurement, mapping, or monitoring of forests worldwide. Invented in 1960, the laser and, a short time later, LiDAR, were found in research and military laboratories. Since the early 2000s, commercial technological developments coupled with an improved understanding of how to manipulate and analyze large amounts of collected data enabled notable scientific and application developments. A diversity of rapidly developing fields especially benefit from communications offered through conferences such as SilviLaser, and LiDAR has been no different. In 2002 the SilviLaser conference series was initiated to bring together those interested in the development and application of LiDAR for forested environments. Now, a little over a decade later, commercial use of LiDAR is common. In this paper – using the deliberations of SilviLaser 2012 as a source of information – we aim to capture aspects of importance to LiDAR users in the forest ecosystems community and to also point to key emerging issues as well as some remaining challenges.

Introduction

SilviLaser 2012 was the 12th in a series of specialized conferences on the use of laser remote sensing for forest characterization. "SilviLaser 2012: First return" marks the 11th year and 12th edition of the conference, the first of which was held in Victoria, British Columbia in 2002. The return to Canada was aimed at bringing together academics, research scientists, and industry representatives from around the world to share their experience in the development and application of LiDAR for forests and other vegetated environments. Co-chaired by Nicholas Coops of the University of British Columbia and Michael Wulder of the Canadian Forest Service, SilviLaser 2012 took place at the Sheraton Wall Centre, Vancouver, Canada, on 16–19 September 2012. Previous conferences have taken place in Canada (2002, 2010), Australia (2002, 2011), Sweden (2003), Germany (2004, 2010), the United States (2005, 2009), Japan (2006), Finland (2007), and the United Kingdom (2008). From the outset, the SilviLaser series of conferences has been collegially developed and volunteer implemented.

Over the last decade, the use of LiDAR to characterize forests has progressed from questions concerning data processing, data quality, and measurement consistency to sophisticated current users' questions regarding the generation of local, regional, continental, and global laser-based information products. Airborne scanning LiDAR data are now considered operational for some forestry applications (in an increasing number of jurisdictions) and continue to provide otherwise unavailable scientific insights through the detailed and novel structural measurements made (Hyyppä et al., 2012). From its inception, the SilviLaser conference series has been international and has garnered strong involvement from commercial agencies. Although government and academic participation dominates, commercial vendors and instrument developers have made a notable contribution.

We also note and acknowledge the differences between LiDAR and airborne laser scanning (ALS) (**Table 1**). Hereafter we follow community convention and use the term LiDAR, unless a specific relevant element dictates otherwise. In this introduction to the SilviLaser 2012 Special Issue, we provide an overview of the key trends and themes

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Table 1. Characteristics of LiDAR and Airborne Laser Scanning.

LiDAR (Light Detection and Ranging)

- refers to the instrument that emits and receives the laser energy (laser ranging unit)
- includes the laser, a time interval meter, and a telescopic receiver
- independent of platform (i.e., terrestrial, airborne, spaceborne) and configuration (i.e., discrete return, full waveform)

Airborne Laser Scanning (ALS)

- refers to a package of instrumentation that includes a LiDAR sensor, a GPS receiver, an inertial measurement unit (IMU), and an onboard computer and data storage devices
- as the name implies, the LiDAR used in an ALS system would be a scanning laser emitter–receiver unit (this type of LiDAR has a built-in scanning mechanism that directs the laser beam across the flight path within an operator specified angle)
- independent of configuration (i.e., discrete return, full waveform)
- distinct from an Airborne Laser Profiler

that have emerged over the last decade. With the SilviLaser 2012 presentations foremost in our minds, we review current and ongoing topics of interest and discuss future challenges.

Multispectral and waveform LiDAR

Although the use of full-waveform LiDAR in vegetation studies has been increasing, it remains unclear if the benefits of the additional information merit the extra cost in data processing and archiving over traditional discrete-return data. Some studies show promising first results, e.g., studies related to physically sound derivation of gap fractions or classification of the understorey vegetation. However, it remains to be seen whether these advantages and the associated requirements for additional specialised processing will be sufficient to encourage data users and surveyors to make the switch to full-waveform LiDAR.

Multispectral LiDAR clearly has the potential to combine the best of two worlds – airborne laser scanning (ALS) and multispectral (MS) imaging. Such a combination overcomes issues such as shadowing (MS) and the interpretation of intensity values (ALS). At the conference it was demonstrated (both by simulation studies and first tests using ground-based prototypes) that multispectral LiDAR can provide vertical profiles of indices such as Normalized Difference Vegetation Index (NDVI) and better differentiation of ground returns from large-footprint data. Ultimately, the technology holds promise to provide structural and physiological information simultaneously and facilitate the formulation of new products, e.g., true effective leaf area index (LAI) as opposed to the plant area index (PAI) that single-wavelength instruments provide.

It is only through physical modeling of LiDAR waveforms that our understanding of the information content of these new datasets will advance, especially as we continue to face a validation paradox for all but the most basic biophysical variables that can be derived from LiDAR. In addition to the indirect link of most validation tools with the environmental variable (e.g., digital hemispherical photographs for LAI), validation over larger areas seems unfeasible. Consequently, we should strive for products that exploit all the information that can be derived from waveforms without linkage to an extensive field dataset (e.g., Armston et al., 2013). Physical modelling is the best way to define, test, and implement such products, just as measuring anything and everything in the virtual environment allows for control and distinction of responses, which is difficult when making measurements in actual forests.

The transition from the lab to operational reality for these new datasets and data products requires changes in data format and storage paradigms. Adoption of the use of PulseWaves open-source format, as an example, has been actively encouraged by the SilviLaser community. Access to the complete metadata for each waveform will enable the expert user to exploit the full wealth of physical information contained in the data, be it for single or multiple-wavelength full-waveform systems.

Terrestrial laser scanning

Although previous SilviLaser conferences have seen increasing interest in terrestrial laser scanning (TLS), the number of papers and posters using TLS in 2012 was remarkable. For the first time, dedicated TLS sessions were included as part of the SilviLaser 2012 program, with topics covering new sensors, algorithm development, and new applications, including developments of autonomous and ultra-portable scanners, dual-wavelength (even hyperspectral) instruments, and mobile systems. In general, the materials illustrated the increasing detail and accuracy with which individual trees and forest stands are being measured and modelled.

The maturity of TLS for forest science and forestry applications remains some years behind that of airborne LiDAR, with much untapped LiDAR potential in TLS as the hardware and methods continue to develop. As this occurs, the acceptance of TLS-based survey methods in a number of application domains is also demonstrably increasing. Plot-wise forest inventory has been a common application for TLS research; however, at SilviLaser 2012 the use of TLS in biomass estimation was more common. Other developing applications areas included characterising structural variation across different forest types and different regions, quantifying fire fuel parameters, detecting inter-tree competition, and structural change detection using multitemporal TLS observations. Further, TLS offers a valuable opportunity for the development and testing of new ideas (e.g., dual- or greater-wavelength systems) that may be later applied to airborne systems. The integration of TLS and ALS data was also touched upon, with early discoveries, complementarity, and potential noted.

A community of practice has been building for a number of years around TLS science through informal collaborations. At SilviLaser 2012, the first meeting of the TLS International Interest Group (TLSIIG) was convened by Professor Alan Strahler from Boston University. A large number of SilviLaser delegates attended and discussed how they might better collaboratively develop and promote their science. Outcomes from the meeting included a TLSIIG web site, which is a common portal for sharing publications, data, and TLS related news stories (http://tlsiig.bu.edu/). A collaborative TLS comparison experiment was also suggested and has since been carried out in Australia, with participating research teams from the United States, the United Kingdom, and Australia. The outcomes from this experiment were presented in Beijing at SilviLaser 2013.

Applications of airborne scanning LiDAR in forest inventory

Due to the on-going importance of and competitiveness amongst industrial forest companies, the sector has been aggressive in seeking to integrate LiDAR into operational practices. From a research perspective, the robustness and repeatability of LiDAR data for forest inventory attribute estimation has been well demonstrated (e.g., Næsset, 2004, 2007; Næsset et al., 2004; Bater et al., 2011; Holopainen et al., 2011). At the operational level, the area-based approach (ABA, Næsset, 2002) has become a standard procedure for processing LiDAR point cloud data to spatial metrics that can be used to create predictive equations for forest inventory attributes (White et al., 2013a). ABA has been at the operational stage for several years and can be considered a proven concept. The foremost advantages of the ABA are precise wall-to-wall predictions of a suite of basic forest inventory variables, such as stem volume, basal area, and height and the capability to scale these estimates to the block, stand, or regional level. As with other model-based estimation techniques, the accuracy and precision of these predictions can be calculated if an independent subset of ground plots is withheld. In principle, LiDAR-based forest inventory does not depend on forest stand boundaries; however, the scalability of LiDAR-based predictions allows them to be seamlessly integrated into existing stand-level inventories.

Forestry has established practices for generating forest inventory information based upon the periodic collection of air photos followed by delineation of the stands. Forest attributes are then interpreted from the aerial images and informed or calibrated by ground measurements. The costs of undertaking a conventional forest inventory are well understood, which necessitated the development of a strong business case for the use of LiDAR. Forest tracts and forest management activities take place across extensive areas, meaning that data collection costs can be considerable. There are economies that reduce costs when flying large areas (see Wulder et al., 2008), but an area multiplier remains. LiDAR notwithstanding, current ALS data (0.5 hits per m^2) acquisition and processing costs for ABA in some jurisdictions are competitive or lower than those of conventional stand inventory methods.

At SilviLaser 2012, multiple sessions focused on operational applications from several nations. Common to these discussions was an expression of the needs to clearly articulate the business drivers and to build robust cases for the acquisition and processing of LiDAR data. Key business drivers were identified including (*i*) reductions in the amount of field work needed to conduct an inventory, (*ii*) reduced costs (or cost avoidance) related to refined road work planning and implementation (based upon the LiDAR derived digital elevation model), (*iii*) the existence of established, LiDAR-based operational inventory practices (i.e., statistical frameworks that integrate airborne LiDAR with ground plot measurements), and (*iv*) the ability to produce value-added products.

The quality and efficiency with which LiDAR can add value to forest inventory and management activities is increasingly well established and documented. Several commercial forest management agencies have taken on business case development. Elements of the business case are aimed at transparently demonstrating what costs are added through incorporation of LiDAR, as well as what cost savings (or cost avoidance) are realized. This can include identifying alterations to current practices that could provide new implementation options or produce information that is not otherwise available, e.g., increased safety through improved planning and targeting of field visits. LiDAR is acknowledged to have greater up-front costs, with projected cost savings to occur throughout an inventory cycle. Projections for cost savings are typically borne more rapidly than projected (Lacroix and Charette, 2013), with additional benefits of the digital data allowing for better accounting for costs. Cost savings, not new information, typically drive support for a LiDAR-assisted or LiDAR-based business model. Also stressed were LiDAR notions of consortia development and working across natural resource and government sectors to share the costs of LiDAR acquisition, with the digital elevation model (DEM) remaining of greatest common interest as a LiDAR-derived product.

At the conference, the notion of rapidly distributing LiDAR data and related inventory products to users was frequently stressed, as well as mechanisms for transparency in product generation, sharing, and feedback. Ongoing challenges facing the operational LiDAR community include (*i*) incorporation of LiDAR into strategic planning processes, (*ii*) enhanced modeling of stream and road interfaces, (*iii*) integration with the range of regulatory processes, and (*iv*) determination of how and when to update forest information (e.g., via repeat LiDAR coverage or photogrammetric methods). The capacity for rapid turnaround of LiDAR acquisition through to product delivery enhances the value of LiDAR (in comparison with typical timelines associated with photo-based inventories). During the conference, one presentation provided the example of consumers waiting for five years for the generation of photo-interpreted products from the mandated provincial agency.

As the technology has matured we have seen the additional value that can obtained from LiDAR beyond tree height and volume. Value added products include, for instance, the capacity to better link mill demands to what is present in the forest such as wood quality metrics including tree sweep, density, and branchiness. Novel forestry indices continue to be generated, including those intended to capture thinning and competition. These indices can be tailored to meet specific needs of a given management issue or to address unique characteristics within a specific region.

In countries with extensive and remote forested areas where only a small proportion of these areas are managed, it is not yet feasible to acquire wall-to-wall ALS data. For example, in the host country, Canada, only a subset of the total forested area is managed for commercial harvesting. Managed forests are predominantly publicly owned and stand sizes are larger than in privately owned forests in Nordic countries. In Canada, countrywide estimates are required and used for national and international reporting obligations, though not necessarily for forest management.

Software

A number of talks and keynotes focused on tool development such as FUSION and LAStools, both of which were well represented and warmly welcomed by the SilviLaser community. These tools, and packages like them, have become essential components of any strategy by LiDAR users to consistently and systematically transform LiDAR point clouds to metrics (e.g., height and density percentiles, height variability, and percent canopy cover). Over the history of the SilviLaser conferences we have moved from the requirement that every LiDAR user must code their own data processing routines to the ready availability of processing tools and products that meet a variety of user needs.

Data integration

A number of presentations focused on data integration. Interestingly, an aerial image derived digital surface model (DSM) offers an intriguing alternative to LiDAR data for area-based predictions of forest inventory attributes (White et al., 2013b). In addition, the use of aerial imagery derived surface models has shown a capacity for forest inventory updates (Vastaranta et al., 2013). A key consideration with aerial imagery derived surface models is that a LiDAR-derived digital terrain model (DTM) is required to normalize elevations to heights above ground. That is, a LiDAR collection must have been undertaken at some previous point in time.

LiDAR-based sampling has been used for forest inventory (without mapping) (Wulder et al., 2012a) with promising results. In LIDAR-based sampling or large-area forest mapping using satellite images, LiDAR-based predictions for forest stand attributes have been used instead of traditional ground plots to provide reference data. Thus, in addition to the use of LiDAR-based forest inventory in the actively managed forest areas, LiDAR-supported forest monitoring is becoming an increasingly important tool in providing forest information for national and international reporting obligations.

Satellite LiDAR

In terms of the technological development, as a community we have an abundance of data sources available for sampling with LiDAR (Wulder et al., 2012b), including profiling discrete return, ALS small-footprint discrete first–last and multi-stop, ALS waveform, ALS photon-counting, Geoscience Laser Altimeter System (GLAS) waveform, and simulated ICESat-2 photon counting systems. In a short time, the community has progressed from access to 2 kHz profiling instruments to today's >300 kHz scanning systems. In terms of grand challenges remaining, the consensus at the conference and the community as a whole is for access to high-quality data from spaceborne LiDAR. Suggested configurations include a near-polar orbiting, processing or off-pointing ($<2°$; not repeat-track), multibeam (e.g., 3, 5, 7 beams), with $\leq$ 30 m footprints, and contiguous-profiling vegetation LiDAR with a ≥ 5 year mission design life. The congeniality and scientific collaborations seen at the various SilviLaser conferences suggests that there exists the potential for international cooperation with regards to the design, construction, and launch of LiDAR space missions. Such cooperation would spread the cost and decrease the likelihood of project cancellation and (or) unnecessarily redundant missions (Durrieu and Nelson, 2013). The technology exists, the science is understood, the markets are well developed, and researchers and students are ready to go. A working satellite LiDAR remains one of the great unmet challenges for forestry LiDAR research and applications, and it is one that we hope is addressed before we reach our 20th anniversary.

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