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# On promoting the use of lidar systems in forest ecosystem research

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## Abstract

*Forest structure is an important driver of ecosystem dynamics, including the exchange of carbon, water and energy between canopies and the atmosphere. Structural descriptors are also used in numerous studies of ecological processes and ecosystem services. Over the last 20+ years, lidar technology has fundamentally changed the way we observe and describe forest structure, and it will continue to impact the ways in which we investigate and monitor the relations between forest structure and functions. Here we present the currently available lidar system types (ground, air, and space-based), we highlight opportunities and challenges associated with each system, as well as challenges associated with a wider use of lidar technology and wider availability of lidar derived products. We also suggest pathways for lidar to further contribute to addressing questions in forest ecosystem science and increase benefits to a wider community of researchers.*

*Keywords: lidar systems, lidar products, forest structure*

## 1. Introduction/historical background

The quantification of forest vegetation structure at various scales is critical for understanding and modelling ecosystem processes like photosynthesis, carbon allocation, water fluxes, energy balance, debris and decomposition, floral and faunal biodiversity, growth and mortality dynamics, and susceptibility to drought/fire/insects (Parker, 1995; Spies, 1998; Shugart, 2000; Shugart *et al.*, 2010). Forest structure can be defined in several ways, including the distribution of all plant parts in space, the vertical distribution of foliage or branching structures, the horizontal height distribution of trees or the distribution of species. Many structural variables are difficult and time consuming to measure in the field and especially in remote, tall, complex, spatially variable or highly sensitive ecosystems. Lidar has proven useful in deriving information about forest structure because of its speed, coverage and ability in describing 3D attributes compared to existing manual methods. The highly detailed 3D positional data provided by lidar systems has revolutionized -and can further expand- the way we consider canopy structure in forest ecosystem science.

Lidar most commonly employs coherent, collimated laser light, with wavelengths used for ranging usually in the near-infrared or green (Wehr and Lohr, 1999). Soon after the invention of lasers in the early 1960s, lidar systems were used in atmospheric science (to retrieve, for example, cloud composition, aerosols, and wind speeds), and for bathymetric surveys from the late 1960s (Hickman and Hogg, 1969). During the following decade, lidar became a tool for terrestrial surveys, and trees in forests were then largely considered as noise in topographic mapping projects (Arp and Tranarg, 1982). But in the mid 1980s, studies began using ultraviolet laser profilers

(Nelson *et al.*, 1984) and green lasers profilers used for bathymetry (Nelson *et al.*, 1988) to retrieve tree heights in forest environments. In the early 1990s, laser profilers and small footprint laser scanners using near-infrared light were used specifically for retrieving the vertical distribution of material within a forest canopy in addition to tree heights (Harding *et al.*, 1994). By the late 1990s, studies proliferated on the use of airborne lidar systems for estimating tree height, stand volume, basal area, tree biomass, and vertical profiles of leaf and wood distribution (Nilsson, 1996; Naesset, 1997; Lefsky *et al.*, 1999). In the early 2000s, a seminal review paper was published by Lefsky *et al.* (2002). Since then, lidar technologies have evolved, and new ground and space based systems with wide-ranging capabilities have emerged. And, as predicted by Lefsky *et al.* (2002), applications have expanded into various fields and led to increased interdisciplinary research collaborations.

Here we present the different types of systems currently available and briefly review research that uses these different lidar systems in forest ecosystem studies. We emphasize that different science questions require information at different spatial and measurement scales, and the choice of lidar system and acquisition protocols are important for deriving the right quality of information. We also identify the main limitations to the use of lidar data or products by non-experts, and propose pathways to address these and further enable benefits from the technology. The paper is mainly intended for non-experts who are looking to integrate products derived from lidar into their research. We focus on two areas of forest ecosystem science: forest ecology and forest productivity. The context in which lidar is used in forestry significantly differs from these two fields because lidar data has become part of most national inventory activities; lidar use in forestry is thus not discussed here (the reader is referred to White *et al.* (2016) for a review on this topic). The aim of the present paper is to summarize the capabilities of different lidar system types for deriving useful information about forest structure, to promote appropriate selection of lidar system for a given application, and to stimulate reflections on ways to increase the benefits of this technology for forest ecosystem research.

## 2. Types of lidar systems

Most common ranging lidars measure the interval between a short-duration transmitted pulse (2-10 nanoseconds) and detection of the reflected return signal ("time-of-flight"). Less common lidar systems use a phase shift approach on continuous wave laser emissions, or single photon counting. By combining a range measurement with a position-orientation system, the three-dimensional location of reflecting surfaces can be determined and registered to a geographic reference frame. Several detection methods are used to characterize the return signal in time-of-flight systems (Harding *et al.*, 2011). Full-waveform lidar digitize the entire time-varying amplitude of the return signal to measure the distribution of different reflecting surfaces illuminated by the laser footprint along its path. Discrete-return lidar identifies and retains a number of ranges for which the reflected laser energy signal exceeds a threshold. For example, current discrete return airborne systems typically record between 5 and 9 separate ranges per emitted laser pulse in forests. Discrete returns from many laser pulses produce a "point cloud" that depicts the spatial organization of reflecting surfaces.

In addition to the ranging method, lidar deployments may be classed based on the type of platform used. Here we identify five primary platform deployment types: 1.) airborne laser scanning (ALS) from a manned aircraft, 2.) unmanned Aerial Vehicle (UAV) laser scanning (ULS), 3.) terrestrial laser scanning (TLS) from a static ground platform, 4.) mobile laser scanning (MLS) from a moving ground platform, and 5.) spaceflight lidar (SLS).

ALS systems are deployed on fixed or rotary wing aircraft most commonly at altitudes of 500 m to 3,000 m using small laser pulse footprint systems. Large footprint systems operate at higher altitudes up to 20,000 m. Recently, the company Optech commercialized a multispectral ALS named the Titan sensor, using lasers in three wavelengths (one green and two infrared). ULS systems are similar to ALS in terms of components, but with miniaturized equipment installed onboard a UAV which typically flies at much lower altitudes (about 50 m to 300 m above ground). UAVs can also be flown using fixed-wing or multi-rotor designs, with rotor systems able to fly at lower speeds and provide higher point density. TLS systems are primarily used for detailed point cloud representations of near-field (< 100 m) targets in forests. The instrument is generally stationary and fixed on a survey tripod, and scans acquired from multiple locations can be combined to increase coverage and minimize occlusions. MLS includes two sub-classes of systems: a first system can be placed in a backpack or on a vehicle to acquire 3D data as the operator is walking through the forest or as the vehicle moves through the forest -these systems typically use a technique called Simultaneous Localization and Mapping (SLAM)-, and a second system called the Portable Canopy Lidar (PCL), which emits lasers only in the upwards direction as the operator carries the lidar system while walking along a transect. SLS systems are deployed onboard satellites. The GLAS system on ICESat-1 was in operation until 2010 and had a 70 m footprint, and new smaller footprint systems from NASA in the 12-25 m range are operational: the Advanced Topographic Laser Altimeter System (ATLAS) on ICESat-2 was launched in September 2018, and the Global Ecosystem Dynamics Investigation (GEDI) installed on the International Space Station (ISS) was launched in December 2018. The Japanese agency JAXA is developing the Multi-footprint Observation Lidar and Imager (MOLI). Descriptions of lidar systems are given below and examples of data provided by the different lidar systems are provided in Figure 1.

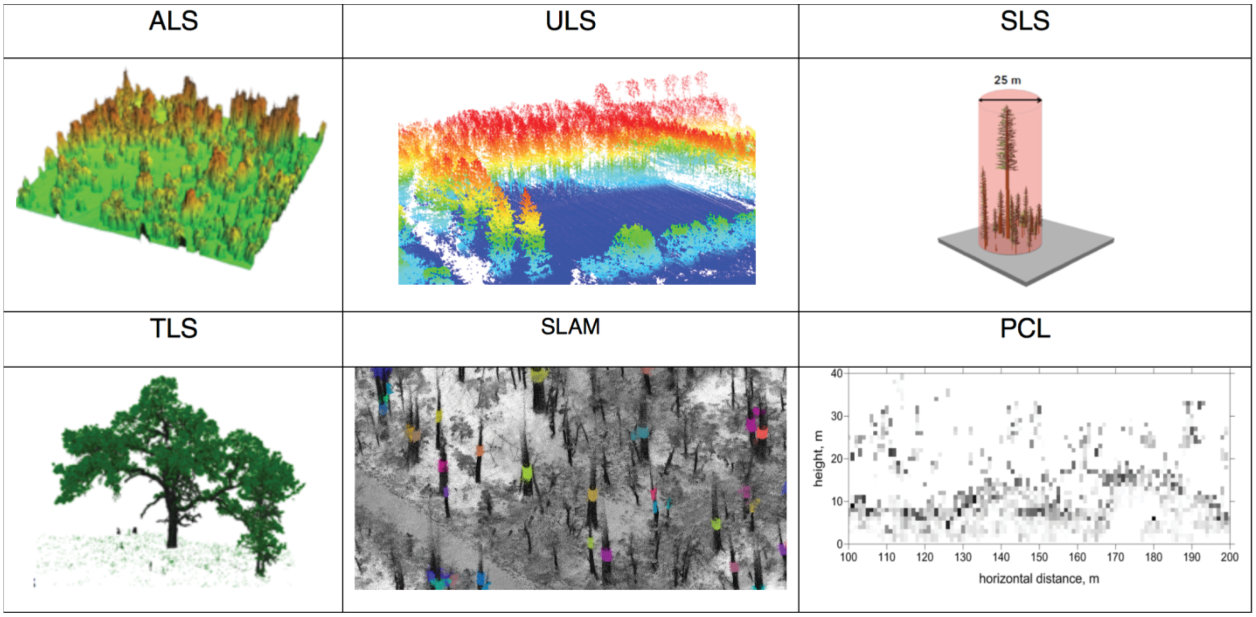

*Figure 1: Examples of data provided by the different lidar systems, identifying the capabilities and resolution of each instrument, and the pulse spacing of an upcoming satellite lidar mission.*

*Images credits: ALS: Biomet lab, UC Berkeley, SLS: GEDI team, University of Maryland, SLAM: Jean-Francois Tremblay, Laval University*

These five lidar system types have three main contrasting characteristics which help understand the opportunities and limitations offered by each system and determine the optimal choice for a given research application: spatial resolution, occlusion and coverage (see table 1). Spatial resolution refers to the level of canopy structural detail which can be resolved from lidar measurements and directly depends on the size of the laser footprint and the spacing separating the footprints. Both the footprint size and the spacing between consecutive pulses increase with distance from the instrument. Occlusion refers to the blocking or shadowing of laser pulses, at least partially, by leaves and branches preventing interception of the pulses by material beyond (Harding *et al.*, 2001), and results in little or no information retrieved from certain canopy areas. The amount of occlusion highly depends on the footprint size, the plant area density (foliage and woody material combined, and their size distribution) and scanning geometry. The location of occluded surface is strongly dependant on the orientation of the laser pulse (see Figure 2), and this can significantly impact applications aimed at reconstructing the canopy to detect gaps, for example, while occlusion may be accounted for or ignored when using statistics relating to points spatial distribution. The coverage refers to the area typically covered by a survey using reasonable financial resources; an analysis of the coverage-cost relationship for each system is presented in Figure 3. On the basis of these characteristics and other considerations, the advantages and disadvantages of the different lidar systems are presented in table 2.

*Table 1: Main characteristics of lidar systems considered*

|  | Resolution |  | Occlusion main location | Typical area coverage | Detection method |
|---|---|---|---|---|---|
|  | Footprint | Spot spacing |  |  |  |
| ALS (small footprint) | 0.1-3 m | 0.2-2 m | Lower canopy | 10-1000 km2 | Discrete/ Full-waveform |
| ALS (large footprint) | 10-30 m | 10-30 m | Lower canopy | 10-1000 km2 | Full-waveform |
| ULS | 0.05-0.1 m | 0.05-0.25 m | Lower canopy | 0.02-10 km2 | Discrete/ Full-waveform |
| TLS | 0.01-0.05 m | 0.005-0.05 m | Upper canopy | 0.01-1 ha | Discrete/ Full-waveform |
| PCL | 0.05 m | 0.01 m | Upper canopy, | 0.02-10 km2 | Discrete |

| | | | | | |
|---|---|---|---|---|---|
| | | | understory and ground | | |
| SLAM | 0.01-0.05 m | 0.005-0.05 m | Upper canopy | 0.25- 5 ha | Discreate |
| SLS | 12-25 m | 60 m/500 m | N/A | Near global | Full-waveform/ photon counting |

*Table 2: Main advantages and disadvantages of lidar systems for mapping forested environments*

| | **Advantages** | **Disadvantages** |
|---|---|---|
| **ALS** | ● Covers relatively large areas in a spatially contiguous manner<br>● Provides direct estimates of canopy roughness, cover fraction, tree height terrain elevation, slope and aspect<br>● GIS-ready raster maps of vegetation height, crown extents, stem locations, LAI and biomass can be generated | ● Limited description of within-canopy structure<br>● Due to high cost to acquire instrument data collection is typically conducted by airborne lidar service providers<br>● Requires the coordination of optimal weather conditions, airborne logistics and a ground support crew |

| | | |
|---|---|---|
| | ● Can be used to monitor disturbance using repeat measurements<br>● Allows scaling from plot to satellite data | |
| **ULS** | ● Matches most advantages of ALS systems except for reduced coverage<br>● Significant increase in detail level of within canopy structure compared with ALS<br>● Higher pulse density compared to ALS<br>● Potentially less expensive than ALS acquisitions (depending on area size)<br>● Can be acquired together with high resolution multispectral or hyperspectral data | ● Coverage of surveys is significantly lower than for ALS<br>● Line of sight government regulation can limit the use of this system in some environments, especially in dense forests<br>● Existing processing methods for ALS data may not all be directly transportable to ULS because of higher resolution and larger off-nadir angles; some methods development may be required<br>● Data collection needs to be contracted out and the currently limited number of service providers results in service not being available in all areas |
| **TLS** | ● Tree to plot level coverage | ● Limited spatial coverage, unless extensive field campaign efforts are deployed |

| | | |
|---|---|---|
| | • Provides detailed information about within canopy structure (lower and middle parts of the canopy)<br>• Possible to separate wood from leaf material within data<br>• Can provide accurate LAI and full 3D foliage distribution within plots<br>• Potential for estimating foliage clumping on the basis of light interception by wood and leaves<br>• Potential use in within-canopy light environment studies as well as studies linking structure with function<br>• Can be used to generate accurate above-ground biomass allometric equations<br>• Provides stem maps, DBH, taper and basal area | • Potential gaps in data, particularly higher up in the canopy and in areas of dense understory/canopy foliage<br>• Field methods are complex, particularly logistics and multiple scans alignment to a common positioning reference system<br>• 3D raw and derived data can be challenging to work with and are not always GIS compatible |
| **PCL** | • Can cover relatively large plot areas | • Limited spatial coverage<br>• Linear transects pattern results in 2D+ data |

| | | |
|---|---|---|
| | - Inexpensive compared to other systems, highly portable<br>- Simple to use and process data<br>- Provides vertical profiles of LAI and within canopy structure along transects<br>- Provides canopy roughness and cover fraction, tree height, stem density | - Potential gaps in data due to occlusion, particularly in dense canopies |
| **SLAM** | - Can cover relatively large plot areas<br>- Can provide full 3D description of the canopy, depending on the type of lidar sensor used | - Systems are relatively expensive and data processing can be complex<br>- When carried out from vehicle, obstacles on the forest floor can limit platform movement direction and speed |
| **SLS** | - Provides near global coverage<br>- Repeated measurements through time of approximately same locations<br>- Provides a description of canopy vertical structure | - Large footprint<br>- Large spaces between consecutive laser footprints for some sensors<br>- Large footprint can generate edge effects |

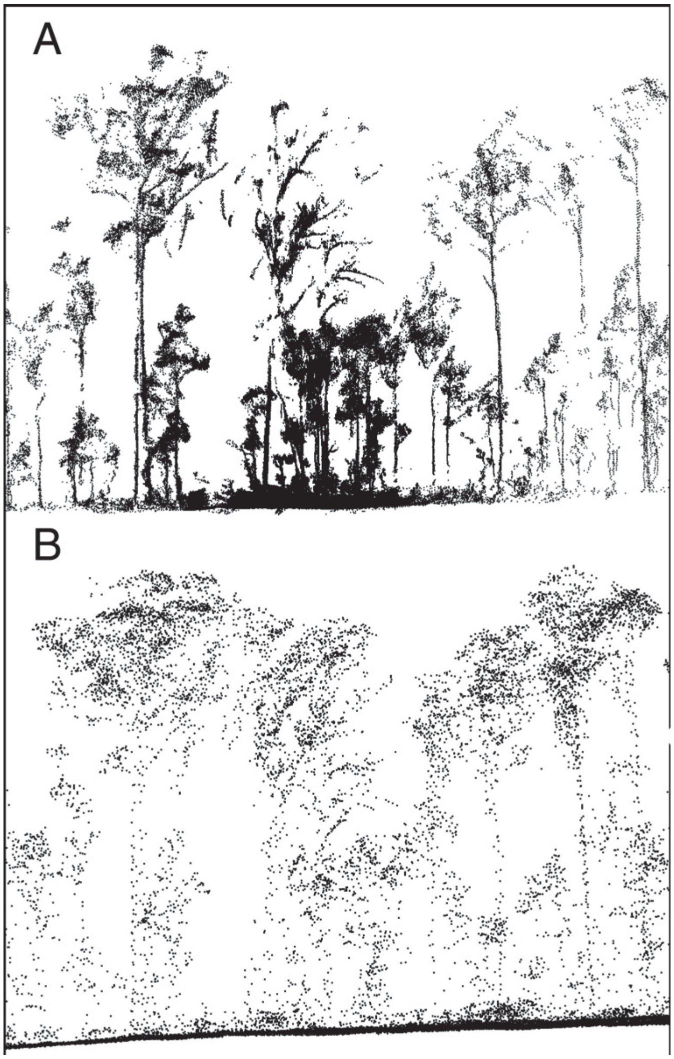

*Figure 2: Differences in top of canopy and within canopy level of detail provided by TLS (A) and ALS (B) lidar systems (from Hopkinson et al. (2013)). The top of the canopy is better described by the ALS system (but with lower point density), while the internal structure is better described by the TLS system.*

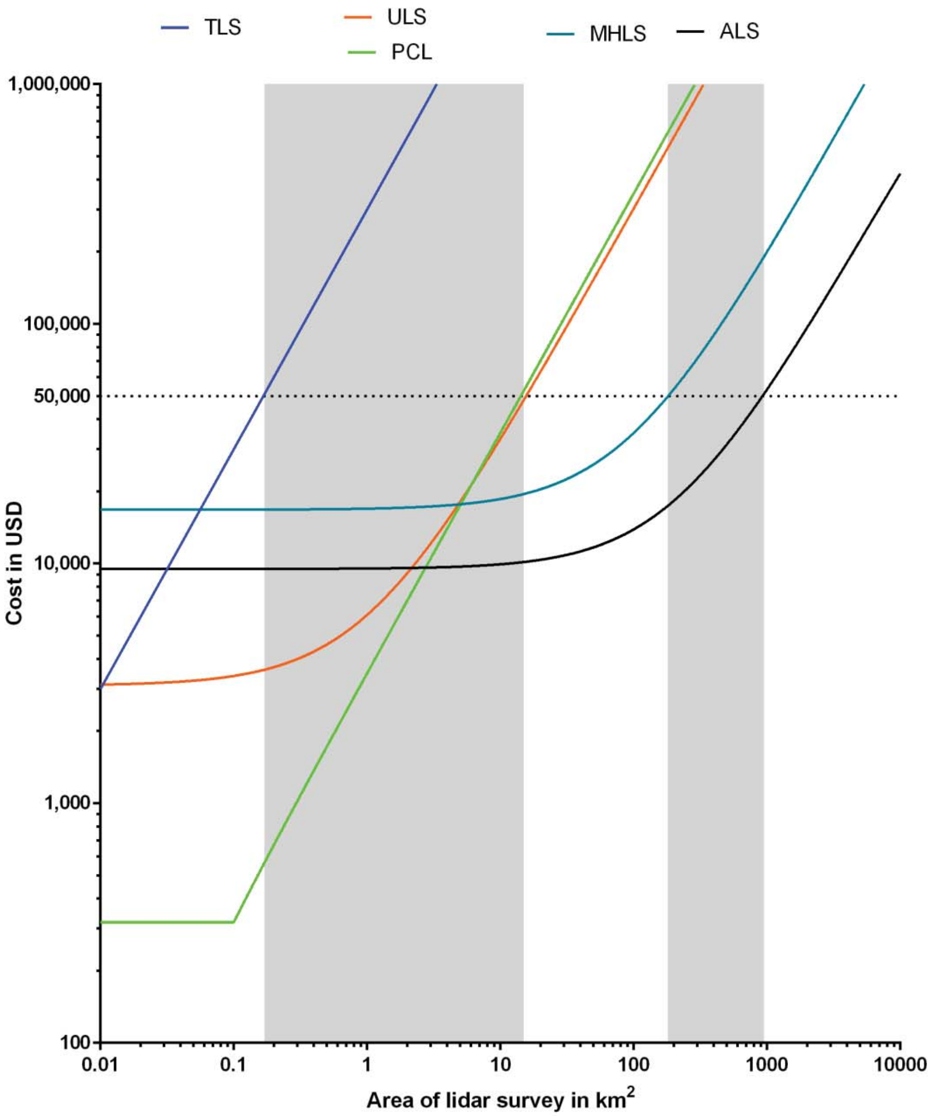

*Figure 3: Illustration of niches for the different lidar systems in terms of cost vs area coverage. Areas in grey are delimited by fixing an acquisition budget of 50,000 USD. The cost estimates assume that the survey is carried out using research staff for the PCL (since the system is simple to operate), and external service providers for TLS (UNAVCO) and airborne systems (private). We also assume that the surveyed area is within 100 km of the service provider location (no*

*transit costs are included). For TLS, the survey is carried out with the aim of a full tree reconstruction (i.e. minimizing occlusion effects). For ULS, it is assumed line of sight can be maintained to about 1 km away from the pilot's position, either from the pilot or spotters on the ground. Average conditions of tree density, canopy closure and ground level obstacles are assumed. Note that for manned helicopter surveys, the cost rises faster than fixed wing as transit distances between the survey site and departure airport increases. SLAM is not shown on the graph as this system has high variability in costs, its niche is estimated to be similar to the PCL and ULS systems. The coverage niches for each system on this basis are thus approximately for TLS: 0-2 ha, PCL and ULS: 2ha – 10 km$^2$, MHLS: 10 -200 km$^2$, ALS: 200-1000 km$^2$.*

## 3. Current usage of lidar systems in forest ecosystem science

Lidar offers two types of advantages in forest science applications: (1) it can provide valuable information not accessible using field methods or optical remote sensing observations, and (2) has benefits in terms of speed of data acquisition, data accuracy, costs and coverage compared with traditional methods of acquiring the same information in the field. Lidar can be used for specific research projects at individual sites, or as part of long-term monitoring activities, or for comparative studies across sites. Several networks are using lidar to integrate observations across sites (e.g. Australia's Terrestrial Ecosystem Research Network (TERN) and the US National Ecological Observatory Network (NEON). The following describes an overview of different applications, system use and data derivations.

Characteristics of lidar systems in terms of resolution, pointing, and pulse geometry, as well as current algorithmic capabilities lead to different levels of suitability towards deriving useful products. On the basis of these characteristics and processing capabilities, the suitability of the different lidar systems and their potential for providing useful products in the future (as processing capabilities improve) were subjectively evaluated. The results of this evaluation are presented in table 3, which provides an overview and is not meant to directly support the choice of a given system for deriving a given product, as there are several nuances related to scale and spatial variability which are not represented by the table. For instance, the estimation of above-ground biomass from TLS is generally done at the individual tree level and the accuracy is well characterized at that scale, while biomass from ALS is computed at the tile level (often 400 $m^2$) and the accuracy is influenced by several variables and is not yet fully resolved. The representation of spatial variability can be determinant in the suitability of a product to usefully describe forest structure for a given research application, because by using average conditions without explicit consideration of variation large scale patterns are recognized while smaller scale patterns may be missed (Larson and Churchill, 2012).

*Table 3: Current and potential products derived from different lidar systems. Colours refer to state of progress of research in deriving each product; red: not available, yellow: experimental, requires more research, green: operational but accuracy is not well defined or controlled, blue: operational and accuracy is characterized and satisfactory for most applications. For those colours requiring significantly more research (yellow and green), + and – signs refer to the suitability of the system for deriving a given product + sign refers to the potential to provide product at a scale and accuracy level which is relevant to research questions, hence research in this direction is considered promising, - sign indicates weak suitability of a system to derive a given product. These represent opinions based on a review of the literature and the experience of the co-authors.*

| Retrievable product | Lidar Platform and Measurement Approach | | | | | | |
|---|---|---|---|---|---|---|---|
| | Airborne Laser Scanning (ALS) | | UAV Laser Scanning (ULS) | Terrestrial Laser Scanning (TLS) | Portable Canopy lidar (PCL) | Simultaneous Localization and Mapping (SLAM) | Spaceborne laser scanning (SLS) |
| | Small Footprint (discrete return) | Large footprint (full waveform) | | | | | |
| Ground slope and aspect | 🟦 | 🟦 | 🟦 | 🟩 - | 🟥 | 🟦 | 🟥 |
| Canopy height | 🟦 | 🟦 | 🟩 + | 🟩 + | 🟩 + | 🟥 | 🟩 + |
| Stem map | 🟩 - | 🟥 | 🟨 - | 🟦 | 🟨 - | 🟦 | 🟥 |
| Crown dimensions | 🟩 - | 🟥 | 🟨 + | 🟦 | 🟨 - | 🟥 | 🟥 |
| Percent cover and gap fraction | 🟦 | 🟩 - | 🟨 + | 🟩 + | 🟦 | 🟥 | 🟨 + |
| Leaf area distribution (vertical 2D or complete 3D) | 🟩 + | 🟨 + | 🟨 + | 🟩 + | 🟦 | 🟥 | 🟨 + |
| Leaf Area Index (LAI, 1D) | 🟩 + | 🟨 + | 🟨 + | 🟦 | 🟦 | 🟥 | 🟨 + |
| Above-ground biomass | 🟩 + | 🟩 + | 🟨 + | 🟦 | 🟩 + | 🟩 + | 🟨 + |
| Stem density and basal area | 🟨 - | 🟨 - | 🟨 - | 🟦 | 🟩 - | 🟦 | 🟥 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Foliage clumping | 🟨 - | 🟨 - | 🟨 + | 🟩 + | 🟩 - | 🟥 | 🟥 |
| Gap size distribution and connectivity | 🟨 + | 🟨 + | 🟨 + | 🟨 + | 🟥 | 🟥 | 🟨 + |
| Aerodynamics parameters | 🟩 + | 🟨 - | 🟨 + | 🟩 + | 🟩 + | 🟥 | 🟥 |
| Competition intensity | 🟨 + | 🟥 | 🟨 + | 🟨 + | 🟨 + | 🟨 + | 🟥 |
| Branch architecture | 🟥 | 🟥 | 🟨 + | 🟨 + | 🟥 | 🟥 | 🟥 |

**Forest ecology.** Ecologists relate information about canopy structure to processes such as evolutionary explanations of plant traits, the interconnectivity of plant form and function, dynamics of trees within a forest and their response to disturbances, or dynamics between trees in a forest and non-woody plants and animals. In a general sense, studies of plant trait applications predominantly use information about surface spectral characteristics and are best served by either multispectral lidar or fusion with hyperspectral passive imagery. Co-located lidar studies can provide an important complement to reflectivity information, for example, TLS can be used to map photosynthetic capacity, water content and pigment concentration in 3D from the intensity of the returned laser light (Magney *et al.*, 2014). However, the interactions of laser pulses with plant parts significantly complicate the interpretation of return signal intensity, and multiple wavelength scanners have potential for enabling this interpretation. Two non-commercial TLS multispectral systems (two wavelengths) have been developed to estimate vegetation biochemical properties: the SALCA (Danson *et al.*, 2018) and the DWEL (Li *et al.*, 2018).

Multispectral ALS has been used to map tree species (Budei *et al.*, 2018), ALS is also being used in fusion with hyperspectral data in a process called “laser-guided imaging spectroscopy” (Asner *et al.*, 2017) to map functional diversity within forests by mapping a series of plant traits. ALS and TLS lidar have also been used to estimate fine scale structural parameters to estimate canopy rainfall interception, which can have a significant impact on the water budget (Roth *et al.*, 2007; Van Stan *et al.*, 2017). Woods *et al.* (2018) recently called for additional use of TLS to collect architectural plant traits over a broader range of species and biogeographical regions.

The cost of lidar data acquisitions has made the availability of time series data over specific sites relatively rare. Systems with systematic repeat measurements, such as the SLS, will promote the use of lidar for investigating forest dynamics. Further, lower deployment costs of ULS should favor greater acquisition repeatability. An important consideration in studying ecosystem change from any remote sensing platform, requires that the magnitude of change is greater than the horizontal and vertical accuracy of laser pulse returns (Hopkinson *et al.*, 2008). Another consideration is the time gap between the acquisition of ground validation data and the airborne data, as greater gaps in time between field validation data collection and a lidar survey can introduce significant biases in model development, particularly within dynamic forest environments.

Significant efforts are being deployed to use lidar for estimating above-ground biomass at different scales using ground, airborne and spaceflight systems. Discrete lidar had been used to estimate biomass based on identifying individual tree features such as treetop height and positions, or by identifying mean height and canopy top metrics (Nelson *et al.*, 1988; Popescu *et al.*, 2003; Asner and Mascaro, 2014). Full waveform lidar from airborne and satellite platforms have estimated biomass using regression techniques based on height and return energy metrics (Drake *et al.*, 2002; Lefsky *et al.*, 2005; Saatchi *et al.*, 2011; Baccini *et al.*, 2012). Current approaches to biomass estimation exploit multiple lidar systems in a spatial scale hierarchy approach. TLS systems have proven efficient at providing accurate estimate of individual tree level wood volumes from a method called Quantitative Structure Modeling (QSM) (Raumonen *et al.*, 2013; Hackenberg *et al.*, 2015). This approach can augment the often costly allometric methods used, as comparisons with destructive field measurements revealed the QSM estimates to be very accurate (Calders *et al.*, 2015).

ALS data have been used for habitat mapping, as vegetation structure is a key determinant of habitat quality for many species (Vierling *et al.*, 2008). It has also been used to assess aspects of biodiversity, as airborne lidar can readily provide estimates of variability in terms of tree heights and vertical layering, indicating diversity in tree species and potentially stand age. ALS has been used to study the movement dynamics in wildlife, which is shown to be highly related to structural complexity (Davies and Asner, 2014; Simonson *et al.*, 2014). Studies on the behaviour of bats in forests have been done using ALS (Froidevaux *et al.*, 2016) and TLS (Yang *et al.*, 2013). Other birds habitat have been studied using the spaceflight GLAS instrument aboard ICESat (Goetz *et al.*, 2014).

**Forest productivity.** Spatial and temporal variability in forest productivity is increasingly observed using the eddy-covariance technique from widely distributed flux towers. Most of the current research using canopy structure information at flux tower sites can be grouped into three components: (1) the interpretation and modeling of carbon, water and energy fluxes, (2) ecosystem dynamics –including disturbance effects, and (3) the process of up-scaling local flux observations to regional patterns. Remote sensing can aid through characterization of forest structure, and can provide spatial data beyond the flux-tower footprint, which helps to extrapolate field based measures to the surrounding land rather than just the tower footprint.

When characterising canopy structure at flux tower sites, the main scale of interest is often determined to encompass the tower footprint. However, some of the processes involved in canopy-atmosphere exchanges may require resolution of structural patterns at fine scales to account for scale emergent properties within the flux tower footprint. For example, the radiative transfer of sunlight through canopies is an important driver of those leaf and canopy level processes. Kobayashi *et al.* (2012) used a map of individual tree position and crown dimensions obtained from discrete return ALS to demonstrate the impact of 3D effects in radiative transfer modeling on water and carbon flux modelling. Hardiman *et al.* (2011) linked primary productivity and canopy structure information derived from PCL data; they looked at total LAI and an index of complexity as factors. Stark *et al.* (2012) and Atkins *et al.* (2018) investigated links between structural attributes derived from ALS and TLS and forest productivity. Mitchell *et al.* (2012) used lidar to couple spatial changes in forest structure and variation in evapotranspiration. Morton *et al.* (2016) linked 3D structure and illumination geometry to forest productivity using airborne lidar.

Ecosystem Models can incorporate information on the current ecosystem state, and with local climatic and edaphic information, can make predictions of carbon, water, and energy fluxes at a variety of scales. Individual based models like the Ecosystem Demography (Moorcroft *et al.*, 2001; Medvigy *et al.*, 2009) and MAESTRA (Medlyn, 2004) calculate growth and mortality dynamics at the scale of individual trees, and can make simulations smaller than the footprint of a flux tower up to the regional and global scale. The Ecosystem Demography model (ED2) can simulate vegetation dynamics of individual trees of a particular size and plant functional type, incorporating the full spatially heterogeneous ecosystem state measured in forest inventories. In this context, lidar can be used to test, validate or constrain output from ecosystem models. This was shown in Antonarakis *et al.* (2011) at the La Selva tropical forest, constraining ED2 carbon dynamics through initializing with radar and lidar measurements of biomass and canopy height respectively. A subsequent study by Antonarakis *et al.* (2014) revealed that a combination of ALS and hyperspectral measurements can be successfully used to derive fine-scale forest structure (i.e. individual tree size class distribution) and plant functional type composition to improve biosphere model carbon flux predictions. Fine-scale forest structure has also recently been derived from the GLAS satellite lidar (Antonarakis and Coutiño, 2017).

Lidar can be a useful tool to address the scale mismatch between a field data and satellite imagery pixel scale. The scale of interest for global scale oriented imagery is typically 0.25-1 km. ALS observations are best suited for this application, as well as for future satellite based missions like GEDI. Chasmer *et al.* (2011) used a number of metrics from discrete return ALS to investigate the role of structure heterogeneity within the flux tower footprint. Simard *et al.* (2011) have used tree height data from FLUXNET sites to validate their global tree height map from space-based lidar. Saatchi *et al.* (2011) and Baccini *et al.* (2012) have used ICESat to define above-ground biomass globally, spatially extrapolating lidar-derived biomass using MODIS and SRTM data layers.

Knyazikhin *et al.* (2013) stressed the need to consider the role of within pixel-level canopy structure in the retrieval of leaf nitrogen from passive optical remote sensing.

Further, a very significant type of activity concerns the combination of data from multiple sites to investigate the causes of intra and interannual variability. Existing databases typically include several structure characteristics relating to canopy structure, like LAI and tree density, along with an estimate of uncertainties in these quantities. These structural parameters are updated with a frequency dependent on the level of dynamism and disturbance at each site, and lidar can be useful in providing the parameters estimates.

## 4. Adopting lidar technology: Consider the 4 P's!

A set of decisions and considerations are needed to provide the right lidar-derived product to a given science question in a particular environment; we refer to those as the 4Ps: Platform, Provider, Protocols, and Processing. The 4Ps refer to a set of decisions driving the use of lidar to support research activities: (1) which lidar *platform* is most appropriate for deriving the needed information? (2) Which *provider* will carry out the survey? (3) which *protocols* will be used for the survey, and how will it be conducted? and (4) what tools and *processing* methods will be used to convert raw lidar data into useful information?

**Platform**. Identifying the appropriate lidar platform (i.e. ALS, ULS, TLS, SLAM, PCL, SLS) to derive the right product for a given application often requires exchanges between lidar and application experts. Such interdisciplinary collaboration is essential to maximizing the benefits of lidar technology and identifying new ways of applying lidar information in forest research. This will require optimal choice of platform considering the factors detailed in Tables 1 & 2. For a particular application, one should consider that the most commonly used lidar system may not be the most appropriate.

**Provider**. Research groups interested in acquiring lidar data have several options: (1) develop the expertise internally, (2) establish a collaboration with lidar experts, (3) hire the services of an organisation dedicated to research, or (4) hire the services of a private firm. Public organisations capable of providing a lidar acquisition service are listed as supplementary information in Supplementary material -no provider is generally required for the PCL. One key advantage to using one of these organisations is the expertise they are able to develop internally over time in working with forest researchers, and in adding new data to an existing standardized repository, which does not routinely happen when data is acquired through private firms.

**Protocols**. Acquisition protocols cover a multitude of activities that apply prior to, during, and after data collection. These protocols should be consistent in terms of item to cover, but the approaches and values used will vary depending on the platform used, type of provider, the environment being measured and the required purpose(s) of the data. At the most basic level these protocols ensure the data collected can be registered accurately and precisely to a position in space and time, and can be integrated with other geospatial data sets. The protocols typically cover: specification of area and time sample, sampling locations, required sampling intensity, required ground control and other required ground measurements, instrument calibration checks, instrument settings, meta-data recording, post-processing procedures, data storage and publication. It may be inappropriate to suggest "one size fits all" recommendations for protocols, as these should be set according to site characteristics and study objectives. However, the development of protocol guidelines is needed. Protocols have been developed for standardised field surveys using TLS to match up with traditional forest structure monitoring metrics (Schaefer, 2015) and for the collection of airborne laser scanner data (Quadros and Keysers, 2015), including a standardised workflow (QA4Lidar).

**Processing**. In terms of data processing capabilities, lidar differs significantly from passive satellite remote sensing with regards to oversight. Most satellite remote sensing instruments used in forest ecosystem science have been coordinated and overseen by government or supra-government institutions, and substantial resources are invested in the development of processing algorithms and their documentation, as well as the publication of standard products. Lidar data has so far mainly been acquired through researchers contracting private or public organisations for data acquisition or purchasing a lidar instrument themselves (some even building their own), and there has been little coordination of algorithmic and software development for processing raw data. This results in a current oversight gap in the development of standard products from lidar.

For processing ALS data, several researchers use the LAStools and FUSION software -which do have some functionalities specific for forest environments-, and the R language package LidR (Roussel *et al.*, 2018) is increasingly popular. Within the TLS community, a Research Coordination Network (RCN) grant from the US National Science Foundation was obtained in 2015 at Boston University to help coordinate measurement protocols and processing algorithm development. A French community has also been organising around a software tool called Computree, which includes one of the two existing Quantitative Structure Modeling (QSM) softwares for estimating individual tree volume (Simpletree); the other being developed by Raumonen *et al.* (2013). Other useful TLS software packages include 3D forest (Trochta *et al.*, 2017), FORESTR (Atkins *et al.*, 2018), and Pylidar (www.pylidar.org). The ULS being a very recent system, there are currently no specific processing tools for processing ULS data in forests that we are currently aware of. The PCL data is somewhat straightforward to process, and processing tools are freely available. The use of simultaneous Localization and Mapping (SLAM) systems in forests is also relatively recent. These complex systems usually combine Inertial Monitoring Units (IMU) and advanced algorithms to account for the platform movement during the lidar acquisition without good GPS signal under the tree canopy. Their use in forests is likely to significantly increase as the technology evolves, equipment costs decrease, and data processing tools availability increases. For many of the products derived from lidar presented here, access is still somewhat limited to groups having remote sensing as their main field of expertise, they are not yet widely available to non-expert groups and not yet routinely used across sites in observational networks.

We suggest that two main factors related to the 4 Ps currently hamper the adoption of the technology and integration within research methods. First, most lidar surveys are relatively expensive, and the resources invested often result in limited sharing of raw lidar data and derived products (when surveys are performed by a private firm there may also be a legal limitation on data sharing). Second, software processing tools are relatively slow to become widely available. Although software is now available for deriving simpler products like canopy height and stem maps, the more complex algorithms used to derive products like crown dimensions, LAI and biomass are not routinely available. We suggest that this results from limited coordination in the development of algorithmic tools and acquisition protocols. Also, efforts from remote sensing research groups are currently aimed towards publishing new applications and novel ideas –where the greater value is currently placed-, and there is little in terms of incentives to develop standardized acquisition protocols and processing tools for the wider community to use.

## 5. A path forward for promoting lidar usage: beyond pretty pictures

**Key Spatially Explicit Products.** Observations from lidar provide a unique capacity to inform new understanding, mechanistic-based modeling and management of forests. However, the measures currently used are mostly single-valued, summarizing the spatial variation of actual canopy structure into one number. Often, a single value of LAI, canopy height or gap fraction is taken to characterize the whole. Yet vegetation structure is enormously variable at various scales - those variations are fundamental components of structure. One of the ground-breaking capacities of lidar is the ability to characterize this variation of object locations in 3 dimensions. While ignoring this variation was once necessary and understandable, it is no longer a restriction. Paying more explicit attention to variation is important for several reasons. For example, many processes of interest operate over ranges smaller than the whole-canopy scale. Also, many important vegetation processes are fundamentally non-linear: canopy light declines exponentially with increasing leaf area and photosynthesis has a curvilinear relation with radiation. Some of the key spatially explicit products which could be the focus of standardisation and sharing from table 3 are canopy heights models, gap distribution and connectivity, leaf area vertical distribution and horizontal heterogeneity, and above-ground biomass. Other products listed in table 3 are at a relatively early development/research stage and processing methods are not yet mature.

**Using the appropriate methodology**. A match between the lidar system used and the science or management question asked is critical. As detailed in section 4, for any given new application, a clear identification of the motivating purpose will inform the choice of lidar platform, appropriate provider, acquisition protocol and data processing. For example, airborne- and space-borne laser scanning (ALS, SLS) are unparalleled for large scale sampling of outer canopy features and for the up-scaling of correlated structures and functions. Gap distribution and connectivity can be derived from ALS, improved interpretation of full-waveform data is particularly promising to this end (Hancock *et al.*, 2017). Terrestrial Laser Scanning (TLS) provides enormous detail about interior canopy features, and is a natural choice for studies of stem allometry and biomass, simulation of light environments, testing of photosynthesis and production models. The potential of TLS to distinguish leaves from wood in mapping of leaf area should be further exploited (Béland *et al.*, 2014a; Vicari *et al.*, 2019). As described, between these extremes are other systems appropriate for other scales of study or repeatability frequency. We emphasize that different lidar systems can be combined to exploit the advantages provided by each, for example TLS measurements can enable the calibration/validation of products derived from airborne or satellite systems.

**Tools and Technology Transfer.** Processing tools are fundamental for reaping the benefits of lidar for forest science. The immense raw data sets are not useful in themselves – they require a great deal of manipulation to yield useful information. Tools for effecting such processing are often time-consuming to develop – they represent an important resource for the lidar community. Several research groups have produced open-source code to analyze lidar data of various sorts (Béland *et al.*, 2014b; Hackenberg *et al.*, 2015; Trochta *et al.*, 2017; Atkins *et al.*, 2018). We encourage the development, ready distribution and testing of cost-free, operational and well-documented approaches for processing lidar data. It is important that these community efforts be professionally recognized and acknowledged.

Once limited in coverage and availability, lidar data of many sorts are now publicly accessible on data sharing platforms – providing such data is mandatory for some funding programs (e.g., NASA Carbon Monitoring System). Some notable data repository currently hosting ground and airborne lidar data include the Oak Ridge National Laboratory Distributed Active Archive Center (daac.ornl.gov), the OpenTopography initiative (opentopo.sdsc.edu/lidar) and the Australian TERN AusCover (www.auscover.org.au). Further systematic sharing of lidar data used in forest ecosystem research should be encouraged. For example, intercomparison across sites and data types holds great potential to reveal patterns at macrosystem scales. As progress is made on the challenges identified here, the forest ecosystem research community and ecological monitoring networks (e.g., LTER, ICOS, Ameriflux, NEON and TERN) will have greater access to standard and useful products derived from lidar.

**Cooperation and coordination**. Collaborative and cooperative efforts have a particularly great potential for leveraging research in the lidar community. Interdisciplinary connections are favored by activities such as workshops or meetings linking the lidar and forest ecology communities. Recent examples are the "Terrestrial Laser Scanning for Ecology" workshop held during the Australian Society for Ecology (ESA) annual conference in December 2016, and “The terrestrial laser scanning revolution in forest ecology” meeting hosted by the Royal Society held in the UK in February 2017.

Research coordination networks are also valuable for furthering integrated efforts, and we recommend networks be created to cover all lidar platforms. Such a network should aim to promote (1) linkage between lidar experts working in forest ecosystems, (2) coordination of algorithmic efforts for producing a set of standard products in forests from lidar, and (3) the development of best practices in acquisition protocols for the different systems in different forest types. Initiatives to enable the sharing of lidar data are also needed, including establishing exclusive use periods for some data sources on which the community agrees. Cooperative networks could also further progress on ways to integrate different sorts of lidar. For example, a focused study on a well-studied site (with a history of research on habitat, animals, biomass, carbon exchange and so forth) would provide a test case to study interaction of various sorts of measurement systems.

**New Thinking about Structure.** Many recent uses of lidar involve applications of novel data but using standard methodologies. Clearly, more detail on structure will help fine-tune many descriptive characterizations of forests. But there are few models that require spatial detail and information about variation. Progress is needed in thinking of new ways to make use of small-scale spatially explicit products in predicting ensemble behaviors. We need new hypothesis connecting the 3D structural features revealed by lidar to processes of interest, as well as a new class of models designed to explicitly incorporate lidar information and deal with the implied complexities. We suggest that funding agencies include in their calls for proposals the need for new hypothesis linking spatially varying structural information with forest ecosystem processes. As progress is made on this and other challenges presented here, we believe the forest ecosystem research community and ecological monitoring networks, like LTER, ICOS, Ameriflux, NEON and TERN, will have greater access to -the right- lidar-derived products.

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## References

Antonarakis, A., Munger, J., Moorcroft, P., 2014. Imaging spectroscopy-and lidar-derived estimates of canopy composition and structure to improve predictions of forest carbon fluxes and ecosystem dynamics. Geophys. Res. Lett. 41, 2535-2542.
Antonarakis, A.S., Coutiño, A.G., 2017. Regional carbon predictions in a temperate forest using satellite lidar. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 10, 4954-4960.
Antonarakis, A.S., Saatchi, S.S., Chazdon, R.L., Moorcroft, P.R., 2011. Using Lidar and Radar measurements to constrain predictions of forest ecosystem structure and function. Ecol. Appl. 21, 1120-1137.
Arp, H., Tranarg, C., 1982. Mapping in tropical forests: a new approach using the laser APR [Airborne Profile Recorder]. Photogramm. Eng. Remote Sensing.
Asner, G., Martin, R., Knapp, D., Tupayachi, R., Anderson, C., Sinca, F., Vaughn, N., Llactayo, W., 2017. Airborne laser-guided imaging spectroscopy to map forest trait diversity and guide conservation. Science 355, 385-389.
Asner, G.P., Mascaro, J., 2014. Mapping tropical forest carbon: Calibrating plot estimates to a simple LiDAR metric. Remote Sens. Environ. 140, 614-624.
Atkins, J.W., Bohrer, G., Fahey, R.T., Hardiman, B.S., Morin, T.H., Stovall, A.E.L., Zimmerman, N., Gough, C.M., Goslee, S., 2018. Quantifying vegetation and canopy structural

complexity from terrestrial LiDAR data using the forestr r package. Methods in Ecology and Evolution.

Baccini, A., Goetz, S., Walker, W., Laporte, N., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P., Dubayah, R., Friedl, M., 2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. Nature Climate Change 2, 182.

Béland, M., Baldocchi, D.D., Widlowski, J.-L., Fournier, R.A., Verstraete, M.M., 2014a. On seeing the wood from the leaves and the role of voxel size in determining leaf area distribution of forests with terrestrial LiDAR. Agric. For. Meteorol. 184, 82-97.

Béland, M., Widlowski, J.-L., Fournier, R.A., 2014b. A model for deriving voxel-level tree leaf area density estimates from ground-based LiDAR. Environ. Model. Software 51, 184-189.

Budei, B.C., St-Onge, B., Hopkinson, C., Audet, F.-A., 2018. Identifying the genus or species of individual trees using a three-wavelength airborne lidar system. Remote Sens. Environ. 204, 632-647.

Calders, K., Newnham, G., Burt, A., Murphy, S., Raumonen, P., Herold, M., Culvenor, D., Avitabile, V., Disney, M., Armston, J., 2015. Nondestructive estimates of above-ground biomass using terrestrial laser scanning. Methods in Ecology and Evolution 6, 198-208.

Chasmer, L., Kljun, N., Hopkinson, C., Brown, S., Milne, T., Giroux, K., Barr, A., Devito, K., Creed, I., Petrone, R., 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.

Danson, F.M., Sasse, F., Schofield, L.A., 2018. Spectral and spatial information from a novel dual-wavelength full-waveform terrestrial laser scanner for forest ecology. Interface Focus 8, 20170049.

Davies, A.B., Asner, G.P., 2014. Advances in animal ecology from 3D-LiDAR ecosystem mapping. Trends Ecol. Evol. 29, 681-691.

Drake, J.B., Dubayah, R.O., Clark, D.B., Knox, R.G., Blair, J.B., Hofton, M.A., Chazdon, R.L., Weishampel, J.F., Prince, S., 2002. Estimation of tropical forest structural characteristics using large-footprint lidar. Remote Sens. Environ. 79, 305-319.

Froidevaux, J.S.P., Zellweger, F., Bollmann, K., Jones, G., Obrist, M.K., 2016. From field surveys to LiDAR: Shining a light on how bats respond to forest structure. Remote Sens. Environ. 175, 242-250.

Goetz, S.J., Sun, M., Zolkos, S., Hansen, A., Dubayah, R., 2014. The relative importance of climate and vegetation properties on patterns of North American breeding bird species richness. Environmental Research Letters 9, 034013.

Hackenberg, J., Spiecker, H., Calders, K., Disney, M., Raumonen, P., 2015. SimpleTree—an efficient open source tool to build tree models from TLS clouds. Forests 6, 4245-4294.

Hancock, S., Anderson, K., Disney, M., Gaston, K.J., 2017. Measurement of fine-spatial-resolution 3D vegetation structure with airborne waveform lidar: Calibration and validation with voxelised terrestrial lidar. Remote Sens. Environ. 188, 37-50.

Hardiman, B.S., Bohrer, G., Gough, C.M., Vogel, C.S., Curtis, P.S., 2011. The role of canopy structural complexity in wood net primary production of a maturing northern deciduous forest. Ecology 92, 1818-1827.

Harding, D.J., Blair, J., Garvin, J.B., Lawrence, W.T., 1994. Laser altimetry waveform measurement of vegetation canopy structure. In, Geoscience and Remote Sensing Symposium, 1994. IGARSS'94. Surface and Atmospheric Remote Sensing: Technologies, Data Analysis and Interpretation., International. IEEE, pp. 1251-1253.

Harding, D.J., Dabney, P.W., Valett, S., 2011. Polarimetric, two-color, photon-counting laser altimeter measurements of forest canopy structure. In, International Symposium on Lidar and Radar Mapping Technologies. International Society for Optics and Photonics, pp. 828629-828629-828610.

Harding, D.J., Lefsky, M.A., Parker, G.G., Blair, J.B., 2001. Laser altimeter canopy height profiles - Methods and validation for closed-canopy, broadleaf forests. Remote Sens. Environ. 76, 283-297.

Hickman, G.D., Hogg, J.E., 1969. Application of an airborne pulsed laser for near shore bathymetric measurements. Remote Sens. Environ. 1, 47-58.

Hopkinson, C., Chasmer, L., Hall, R., 2008. The uncertainty in conifer plantation growth prediction from multi-temporal lidar datasets. Remote Sens. Environ. 112, 1168-1180.

Knyazikhin, Y., Schull, M.A., Stenberg, P., Mottus, M., Rautiainen, M., Yang, Y., Marshak, A., Carmona, P.L., Kaufmann, R.K., Lewis, P., Disney, M.I., Vanderbilt, V., Davis, A.B., Baret, F., Jacquemoud, S., Lyapustin, A., Myneni, R.B., 2013. Hyperspectral remote sensing of foliar nitrogen content. Proceedings of the National Academy of Sciences of the United States of America 110, E185-E192.

Kobayashi, H., Baldocchi, D.D., Ryu, Y., Chen, Q., Ma, S., Osuna, J.L., Ustin, S.L., 2012. Modeling energy and carbon fluxes in a heterogeneous oak woodland: A three-dimensional approach. Agric. For. Meteorol. 152, 83-100.

Larson, A.J., Churchill, D., 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. For. Ecol. Manage. 267, 74-92.

Lefsky, M.A., Cohen, W.B., Acker, S.A., Parker, G.G., Spies, T.A., Harding, D., 1999. Lidar remote sensing of the canopy structure and biophysical properties of Douglas-fir western hemlock forests. Remote Sens. Environ. 70, 339-361.

Lefsky, M.A., Cohen, W.B., Parker, G.G., Harding, D.J., 2002. Lidar remote sensing for ecosystem studies. Bioscience 52, 19-30.

Lefsky, M.A., Harding, D.J., Keller, M., Cohen, W.B., Carabajal, C.C., Del Bom Espirito-Santo, F., Hunter, M.O., de Oliveira, R., 2005. Estimates of forest canopy height and aboveground biomass using ICESat. Geophys. Res. Lett. 32.

Li, Z., Schaefer, M., Strahler, A., Schaaf, C., Jupp, D., 2018. On the utilization of novel spectral laser scanning for three-dimensional classification of vegetation elements. Interface Focus 8, 20170039.

Magney, T.S., Eusden, S.A., Eitel, J.U.H., Logan, B.A., Jiang, J., Vierling, L.A., 2014. Assessing leaf photoprotective mechanisms using terrestrial LiDAR: towards mapping canopy photosynthetic performance in three dimensions. New Phytol. 201, 344-356.

Medlyn, B., 2004. A maestro retrospective. Forests at the Land–Atmosphere Interface. CAB International, 105-121.

Medvigy, D., Wofsy, S.C., Munger, J.W., Hollinger, D.Y., Moorcroft, P.R., 2009. Mechanistic scaling of ecosystem function and dynamics in space and time: Ecosystem Demography model version 2. Journal of Geophysical Research-Biogeosciences 114.

Mitchell, P.J., Lane, P.N., Benyon, R.G., 2012. Capturing within catchment variation in evapotranspiration from montane forests using LiDAR canopy profiles with measured and modelled fluxes of water. Ecohydrology 5, 708-720.

Moorcroft, P.R., Hurtt, G.C., Pacala, S.W., 2001. A method for scaling vegetation dynamics: The ecosystem demography model (ED). Ecol. Monogr. 71, 557-585.

Morton, D.C., Rubio, J., Cook, B.D., Gastellu-Etchegorry, J.-P., Longo, M., Choi, H., Hunter, M., Keller, M., 2016. Amazon forest structure generates diurnal and seasonal variability in light utilization. Biogeosciences 13, 2195-2206.

Naesset, E., 1997. Estimating timber volume of forest stands using airborne laser scanner data. Remote Sens. Environ. 61, 246-253.

Nelson, R., Krabill, W., MacLean, G., 1984. Determining forest canopy characteristics using airborne laser data. Remote Sens. Environ. 15, 201-212.

Nelson, R., Krabill, W., Tonelli, J., 1988. Estimating forest biomass and volume using airborne laser data. Remote Sens. Environ. 24, 247-267.

Nilsson, M., 1996. Estimation of tree heights and stand volume using an airborne lidar system. Remote Sens. Environ. 56, 1-7.

Parker, G.G., 1995. Structure and microclimate of forest canopies. In: ST1 (Ed.), Forest Canopies. Academic Press, California, USA, pp. 73-106.

Popescu, S.C., Wynne, R.H., Nelson, R.F., 2003. Measuring individual tree crown diameter with lidar and assessing its influence on estimating forest volume and biomass. Can. J. Remote Sens. 29, 564-577.

Quadros, N., Keysers, J., 2015. Airborne LiDAR Acquisition and Validation. AusCover Good Practice Guidelines: A technical handbook supporting calibration and validation activities of remotely sensed data products. Version 1.2. TERN AusCover, 268-301.

Raumonen, P., Kaasalainen, M., Åkerblom, M., Kaasalainen, S., Kaartinen, H., Vastaranta, M., Holopainen, M., Disney, M., Lewis, P., 2013. Fast automatic precision tree models from terrestrial laser scanner data. Remote Sensing 5, 491-520.

Roth, B.E., Slatton, K.C., Cohen, M.J., 2007. On the potential for high-resolution lidar to improve rainfall interception estimates in forest ecosystems. Front. Ecol. Environ. 5, 421-428.

Roussel, J.-R., Béland, M., Caspersen, J., Achim, A., 2018. A mathematical framework to describe the effect of beam incidence angle on metrics derived from airborne LiDAR: The case of forest canopies approaching turbid medium behaviour. Remote Sens. Environ. 209, 824-834.

Saatchi, S., Marlier, M., Chazdon, R.L., Clark, D.B., Russell, A.E., 2011. Impact of spatial variability of tropical forest structure on radar estimation of aboveground biomass. Remote Sens. Environ. 115, 2836-2849.

Schaefer, M., 2015. Measurement of above ground biomass. AusCover Good Practice Guidelines: A technical handbook supporting calibration and validation activities of remotely sensed data products. Version 1.1. TERN AusCover, 202-220.

Shugart, H.H., 2000. Importance of structure in the longer-term dynamics of landscapes. Journal of Geophysical Research-Atmospheres 105, 20065-20075.

Shugart, H.H., Saatchi, S., Hall, F.G., 2010. Importance of structure and its measurement in quantifying function of forest ecosystems. Journal of Geophysical Research-Biogeosciences 115.

Simard, M., Pinto, N., Fisher, J.B., Baccini, A., 2011. Mapping forest canopy height globally with spaceborne lidar. Journal of Geophysical Research-Biogeosciences 116.

Simonson, W.D., Allen, H.D., Coomes, D.A., 2014. Applications of airborne lidar for the assessment of animal species diversity. Methods in Ecology and Evolution 5, 719-729.

Spies, T.A., 1998. Forest structure: a key to the ecosystem. Northwest Sci. 72, 34-36.

Stark, S.C., Leitold, V., Wu, J.L., Hunter, M.O., de Castilho, C.V., Costa, F.R.C., McMahon, S.M., Parker, G.G., Shimabukuro, M.T., Lefsky, M.A., Keller, M., Alves, L.F., Schietti, J., Shimabukuro, Y.E., Brandao, D.O., Woodcock, T.K., Higuchi, N., de Camargo, P.B., de Oliveira, R.C., Saleska, S.R., 2012. Amazon forest carbon dynamics predicted by profiles of canopy leaf area and light environment. Ecol. Lett. 15, 1406-1414.

Trochta, J., Krůček, M., Vrška, T., Král, K., 2017. 3D Forest: An application for descriptions of three-dimensional forest structures using terrestrial LiDAR. PloS one 12, e0176871.

Van Stan, J.T., Norman, Z., Meghoo, A., Friesen, J., Hildebrandt, A., Côté, J.-F., Underwood, S.J., Maldonado, G., 2017. Edge-to-stem variability in wet-canopy evaporation from an urban tree row. Boundary-layer meteorology 165, 295-310.

Vicari, M.B., Disney, M., Wilkes, P., Burt, A., Calders, K., Woodgate, W., 2019. Leaf and wood classification framework for terrestrial Li DAR point clouds. Methods in Ecology and Evolution.

Vierling, K.T., Vierling, L.A., Gould, W.A., Martinuzzi, S., Clawges, R.M., 2008. Lidar: shedding new light on habitat characterization and modeling. Front. Ecol. Environ. 6, 90-98.

Wehr, A., Lohr, U., 1999. Airborne laser scanning—an introduction and overview. ISPRS J Photogramm. 54, 68-82.

White, J.C., Coops, N.C., Wulder, M.A., Vastaranta, M., Hilker, T., Tompalski, P., 2016. Remote Sensing Technologies for Enhancing Forest Inventories: A Review. Can. J. Remote Sens., 1-23.

Woods, H.A., Saudreau, M., Pincebourde, S., 2018. Structure is more important than physiology for estimating intracanopy distributions of leaf temperatures. Ecology and evolution 8, 5206-5218.

Yang, X., Schaaf, C., Strahler, A., Kunz, T., Fuller, N., Betke, M., Wu, Z., Wang, Z., Theriault, D., Culvenor, D., Jupp, D., Newnham, G., Lovell, J., 2013. Study of bat flight behavior by combining thermal image analysis with a LiDAR forest reconstruction. Can. J. Remote Sens. 39, S112-S125.

## Supplementary material

List of main publicly funded organisations capable of providing a lidar acquisition service to researchers

| | Organisation name | Instrument | Contact information |
|---|---|---|---|
| ALS | NASA | G-LiHT (Cook et al. 2013). Small footprint, discrete return system, which includes hyperspectral and thermal imaging instruments | gliht.gsfc.nasa.gov |
| | | LVIS (Blair, Rabine & Hofton 1999). Large footprint full-waveform system | lvis.gsfc.nasa.gov |
| | NEON | AOP (Kampe et al. 2010). Full waveform system with hyperspectral imager | www.neonscience.org and data portal data.neonscience.org |
| | NCALM | Optech Titan. Multispectral lidar (3 wavelengths), full waveform recording with hyperspectral imager | ncalm.cive.uh.edu |
| ULS | Air CTEMP | Velodyne lidar | ctemps.org/air-ctemps |
| TLS | UNAVCO | Riegl VZ-400. Full-waveform capable scanner, 1500 nm laser | www.unavco.org |

## References

Blair, J.B., Rabine, D.L. & Hofton, M.A. (1999) The Laser Vegetation Imaging Sensor: a medium-altitude, digitisation-only, airborne laser altimeter for mapping vegetation and topography. *ISPRS JOURNAL OF PHOTOGRAMMETRY AND REMOTE SENSING*, **54,** 115-122.

Cook, B.D., Nelson, R.F., Middleton, E.M., Morton, D.C., McCorkel, J.T., Masek, J.G., Ranson, K.J., Ly, V. & Montesano, P.M. (2013) NASA Goddard's LiDAR, Hyperspectral and Thermal (G-LiHT) Airborne Imager. *Remote Sensing*, **5**.

Kampe, T.U., Johnson, B.R., Kuester, M. & Keller, M. (2010) NEON: the first continental-scale ecological observatory with airborne remote sensing of vegetation canopy biochemistry and structure. *Journal of Applied Remote Sensing*, **4,** 043510-043510-043524.