White Paper – On the Use of LiDAR Data at AmeriFlux Sites

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1. Executive summary

Purpose of the white paper

Our aim is to inform the AmeriFlux community on existing and upcoming LiDAR technologies (atmospheric Doppler or Raman LiDAR often deployed at flux sites are not considered here), how it is currently used at flux sites, and how we believe it could, in the future, further contribute to the AmeriFlux vision. Heterogeneity in vegetation and ground properties at various spatial scales is omnipresent at flux sites, and 3D mapping of canopy, understory, and ground surface can help move the science forward.

LiDAR technology in a nutshell

LiDAR measurements can provide information about vegetation structure, e.g., the vertical and horizontal organization of plant material through the canopy and understory, as well as ground surface elevation. By combining a range measurement with a system for accurate instrument position and laser orientation the three-dimensional location of reflecting surfaces can be determined and referenced to a geographic standard. The LiDAR systems considered here operate on the same principle: emitted laser pulses intercept a target and a portion of the energy is reflected back to the instrument where it is detected. These systems discussed include: airborne laser scanning (ALS), terrestrial laser scanning (TLS), and portable canopy LiDAR (PCL).

ALS systems are deployed on fixed wing aircraft most commonly at altitudes between 0.5 to 3 km using 'small footprint' (0.1− 3 m) systems. Several 'large footprint' (10 to 30 m) systems operating at higher altitudes up to 20 km have also been developed for research applications. TLS systems typically operate at short range (meters to 100's of m), they have cm-scale footprints (diameter of laser pulse), and spacing between consecutive pulses vary on the order of mms to cms. Their primary use is detailed, point cloud representations of near-field targets. TLS can provide a full 3-D representation of the internal canopy structure. The instrument is generally stationary and is fixed on a survey tripod about 1.5 m above ground. PCL systems record the range to targets as they are carried by an operator along transects, most often pointing the laser beam upward. The systems use relatively low cost, non-scanning laser range finders.

Table 1: Main advantages and disadvantages of the considered LiDAR systems with regards to forested environments

Advantages	
ALS	- Covers the entire flux tower footprint area (and beyond) in a spatially continuous manner - Provides direct estimates of canopy roughness, cover fraction, tree height (including standard deviation), and terrain slope and aspect - GIS-ready raster maps of crown extents, stem locations, LAI and biomass can be generated for many ecosystems - Can be used to monitor disturbances within the footprint using relatively comparable datasets through time - Allows direct scaling from plot or footprint to satellite data resolution and cover
TLS	- Can provide accurate LAI and foliage clumping estimates on the basis of wood and leaf light interception separation and full 3D foliage distribution within plots - Potential use in within canopy light environment studies as well as studies linking structure with functions - Can be used to generate accurate above-ground biomass allometric equations - Provides stem maps, DBH, taper and basal area - Provides detailed information about within canopy structure - Many TLS systems are commercially available for purchase or rental and can be easily operated
PCL	- Relatively inexpensive, highly portable, simple use and data processing - Provides vertical profiles of LAI and within canopy structure along transects - Provides canopy roughness and cover fraction at the flux tower footprint scale
Disadvantages	
ALS	- Limited description of within canopy structure, particularly at understory level - Typically little or no stem or taper information contained in ALS point cloud - High cost to acquire instrument, and data collection is typically contracted out - Requires the coordination of optimal weather conditions, airborne logistics and a ground support crew
TLS	- Limited spatial coverage (typical limit is forest plot scale ~ 25 ×25 m^2 - Potential gaps in data, particularly higher up in the canopy and in areas of dense understory/canopy foliage - Field methods are complex, particularly logistics and multiple scans alignment to a common positioning reference system - 3D raw and derived data can be challenging to work with and are not always GIS compatible
PCL	- Limited spatial coverage, linear transects pattern results in 2D+ data - Potential gaps in data, particularly in dense canopies

Table 2: Products derived by each LiDAR system. Colors refer to **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.

Retrievable metric	LIDAR Platform and Measurement Approach			
	Terrestrial Laser Scanning (TLS)	Airborne Laser Scanning (ALS)		Portable Canopy LiDAR (PCL)
		Small Footprint	Large footprint	
Ground slope and aspect				
Canopy height				
Stem map				
Crown dimensions				
Percent cover				
Leaf area distribution (vertical or complete 3D)				
Leaf Area Index (LAI)				
Biomass				
Stem density and basal area				
Foliage clumping				
Aerodynamics parameters				

Note that the interpretation of Table 2 requires further nuancing; for example, biomass can be accurately retrieved from TLS, but currently only at the individual tree - to plot- level, while ALS-based biomass estimates over areas typically covering the entire flux tower footprint (and beyond). Hence TLS and ALS are complementary with regards to biomass, since accurate allometric relationships can be derived from TLS and used with ALS to scale up to the footprint, stand or ecosystem level. The accuracy of the products derived from TLS, PCL and ALS can also differ significantly.

Use of LiDAR within AmeriFlux activities

In a general sense, the use of LiDAR data at AmeriFlux sites is expected to: (1) describe canopy structure (e.g., tree height, leaf area, biomass) locally for each site, and assess change in canopy structure through repeated sampling, (2) provide greater geometric detail for model hierarchy testing aimed at improving estimates of radiative transfer as used for photosynthesis and energy fluxes in models of land atmosphere interactions, (3) improve understanding of relations between spatial heterogeneity and ecosystem dynamics, and (4) improve capacities to interpret fluxes locally, as well as upscale fluxes to global level and validate satellite product. A survey conducted in 2012 indicates that LiDAR data

is often not exploited to its full potential; a limited number of products are derived from each dataset, the data is rarely shared, and acquisitions are made for specific purposes while they could benefit a range of studies.

While sites within the Ameriflux network have a common goal, they have different characteristics and contexts of operation. These differences must be considered when discussing the proper use of LiDAR technology, since they may influence the preferred type of LiDAR system, the acquisition and processing methods, and the revisit time. For example, Ameriflux's core sites may concentrate a greater proportion of research activities, while other sites aim specifically at investigating the effect of disturbances, or contribute to a gradient of climatic conditions. In general, sites thus have varied lifetimes, varied intensities in the suite of measurements collected (e.g., sapflow, soil, phenology), and aim to address different research questions locally (e.g., integrating measurements and modeling, flux partitioning) while still contributing to synthesis studies through populating the AmeriFlux database, including the BADM (Biological, Ancillary, Disturbance and Metadata) template. Consequently, LiDAR can be expected to meet information needs common to all sites to populate the BADM database (e.g., tree height, tree cover fraction, biomass), but also provide adapted solutions to specific sites where particular science questions are asked, particular complementary measurements are made, or where structure temporal dynamism in high. Thereupon, LiDAR can serve two distinct purposes at flux sites:

- Inventory type structure descriptions to populate BADM database, monitor change therein and allow cross-system comparisons
- Feeding specific research questions, e.g.:
    - Linking process modeling and site measurements
    - Linking flux measurements with large scale passive satellite remote sensing

Recommendations for future action

Considering that the selection of LiDAR systems, acquisition protocols and processing methods should be set accordingly to site characteristics, AmeriFlux would benefit from **building expertise** on LiDAR acquisition and processing methods specifically suited for flux research needs. This can be achieved in two ways:

1. Strengthen collaboration with two NSF funded organisations mandated to promote the use of LiDAR technology in scientific research: NCALM for ALS work and UNAVCO for TLS work. Both organisations have state of the art instruments and competent permanent staff experienced in working with scientists from various fields. Collaborative links with NEON, which operates ALS systems, should also be considered.
2. Support an international LiDAR working group with a mandate to develop LiDAR acquisition protocols, advise on data processing methods, and develop data and products sharing policies. The working group should have strong ties with flux site researchers to promote a mutual understanding across the disciplines.

Several scientific questions require information on finer scale provided by TLS, and it is our opinion that making such information available to researchers will improve capacities for addressing ecosystem questions at the appropriate scales. We thus recommend a multi-scale approach to LiDAR data acquisition over AmeriFlux sites, making use of the different currently available LiDAR systems. This approach would allow the calibration and validation of ALS products, as well as provide a basis for interpreting full-waveform LiDAR data from ALS and from upcoming space flight lidar systems (SLS) such as the GEDI LiDAR onboard the International Space Station or the ICESat II mission (see Figure 1). Full-waveform data consists in digitizing the entire time-varying amplitude of the return signal to measure the height distribution of reflecting surfaces illuminated within the laser footprint; it is particularly useful for mapping within canopy structure. Sites with good quality data from above and below canopy have great potential for looking at complementarity and calibration/validation of airborne and spaceflight products. For this reason ground-based and airborne LiDAR should be acquired at the same sites and concomitantly, when possible.

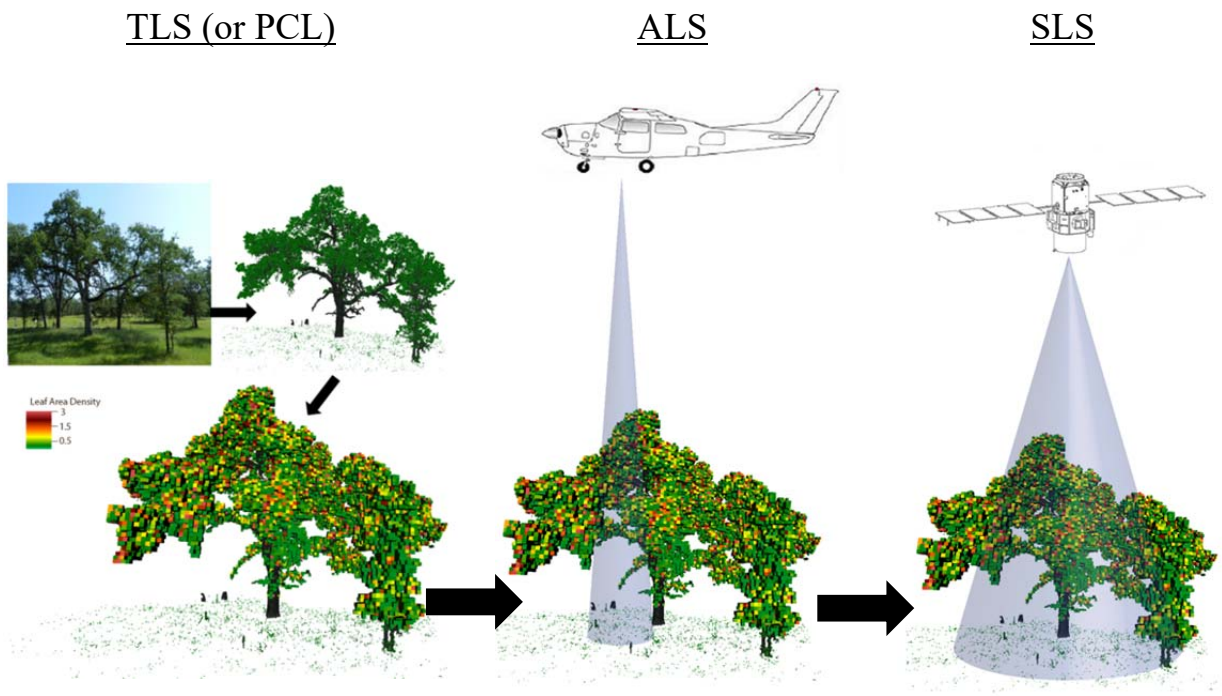


Figure 1 : A LiDAR multiscale design strategy allowing the calibration and validation of products derived from airborne and spaceflight LiDAR products

UAV-based LiDAR can potentially replace ALS at flux sites if only the footprint extent is required by lowering long term monitoring costs and providing higher resolution data while still enabling sufficiently large area coverage. NSF supported Air CTEMPs, a group within the Center for Transformative Environmental Monitoring Programs (CTEMPs), is expected to provide a UAV-based LiDAR measurement service to researchers in the USA by mid-2016. A full assessment of potential and limits of the UAV system is not currently available, but should become available in the near future as US regulations regarding the operation of UAVs are defined, and Air CTEMP further develops its capacities. Given recent progress with this technology, this system is expected to become an ideal airborne LiDAR option for flux sites, and we recommend that AmeriFlux links with researchers using UAV-LiDAR.

2. Introduction

LiDAR measurements can provide information about canopy structure, e.g., the vertical and horizontal organization of plant material, as well as measurements of ground surface topography, all of which are known to influence interactions between the atmosphere and the land surface. In many cases the exact nature of the canopy and understory structure and their influence on carbon and water fluxes is unknown or provisionally modeled. At many sites, information on vegetation structure is inadequate. We believe that LIDAR is an appropriate technology for acquiring that information and further our understanding of those interactions between structure and functions. In this report, we discuss the types of available LiDAR systems, the ways in which these technologies can currently serve the flux community and we suggest some ways they might help in the future. Three types of LiDAR systems will be considered in detail (other existing systems will be briefly discussed): Airborne Laser Scanning (ALS), fixed-location Terrestrial Laser Scanning (TLS), and the Portable Canopy LiDAR (PCL) (Parker et al., 2004) (see Appendix 1 for graphic descriptions of the systems). Unmanned Aerial Vehicle (UAV)-based LiDAR system will also be briefly discussed.

In the fall of 2012 we conducted a simple survey on current LiDAR acquisitions over FLUXNET sites (see Appendix 2). We found, while several sites have LiDAR data, that 1) the data are often not exploited to its full potential, 2) only a limited number of products are derived from the data, 3) the data is often not shared, and 4) acquisitions are typically made for specific purposes but could however benefit a broad range of studies. This white paper proposes pathways to improve the strategic use of the different types of LiDAR systems at AmeriFlux sites.

In a general sense, the use of LiDAR data at AmeriFlux sites is expected to: (1) describe canopy structure locally for each site, (2) improve understanding of links between structure and function across sites, (3) improve understanding of relations between spatial heterogeneity and ecosystem processes, and (4) improve capacities to interpret fluxes locally, as well as upscale fluxes to global level via satellite remote sensing and/or biogeochemical models.

Networks of eddy-covariance observations such as AmeriFlux and the Integrated Carbon Observation System (ICOS) have matured to a point where they can now (1) plan a new generation of long-term ecosystem manipulation experiments, and (2) share material resources and expertise amongst sites. Information requirements at individual sites can now shift from static descriptions of structural variables to temporally dynamic descriptions, as well as create opportunities for economies of scale in the acquisition of LiDAR data. Both of these new conditions have implications for costs-benefits of different LiDAR systems.

3. Organisation of the paper

LiDAR principles of operation and measurement approaches.

The LiDAR systems considered here operate on the same principle: emitted laser pulses intercept a target and a portion of the energy is reflected back to the instrument where it is detected. The distance to the target is determined by the round trip travel time of the pulse and, in some cases, the amount of energy received is recorded. Principle differences between systems are their detection method and the manner in which laser pulses are spatially distributed. These and other instrument attributes are covered in section 4.

Scale as a dominant characteristic of LiDAR systems

A fundamental difference between systems relates to spatial scale, which ultimately translate into the level of detail provided by the measurements, and the surface area covered. Scale and dimensionality issues for different systems are covered in section 5.

LiDAR Research at flux sites

The LiDAR data itself can be processed in numerous ways to derive a range of products describing canopy structure (e.g., Hopkinson et al. (2013); Lefsky et al. (2002)). In order to answer the question "how can LiDAR be best used at AmeriFlux sites?", we need to identify the research questions asked in the studies at AmeriFlux sites that require canopy structure information. These questions may help determine the scale at which canopy structure is needed, and consequently the choice of appropriate LiDAR systems. Because description of variability in canopy structure depends on the scale of observation (Bongers, 2001; Levin, 1992), scientists using LiDAR data should be aware of scale emergent properties within the system being studied to select appropriate LiDAR datasets, and apply the proper scaling laws if needed. Here lies an important challenge in using LiDAR data within terrestrial ecosystem studies. The main research areas and the scale at which they operate are covered in section 6.

LiDAR systems: data acquisition and processing

A significant challenge in using LiDAR in forested and other vegetated environments is to understand what is actually being measured, i.e., how does the emitted light interact with plant parts, how does the LiDAR instrument process the reflected energy, and how these data are then processed. These considerations directly affect which products can be derived from the data, and with which level of accuracy. These technical considerations, along with costs, will be addressed in section 7.

Recommended LiDAR uses at AmeriFlux sites

Sites within the Ameriflux network have a shared goal, but also have different characteristics and contexts of operation which may influence the preferred type of LiDAR system, the acquisition and processing methods, and the revisit time. Recommendations for strategic use of LiDAR data at AmeriFlux sites are provided in section 8.

4. Lidar principles of operation and measurement approaches

LiDAR is an active remote sensing approach using laser light to measure three properties of reflecting targets that are of relevance to AmeriFlux objectives; range (distance), velocity and composition. This document addresses ranging LiDAR systems that are used to measure topography and forest canopy structure. Ranging most commonly employs coherent, collimated laser light. Wavelengths used for ranging are usually near-infrared or green due to the availability of appropriate laser sources. Ranging LiDARs have been developed that use two approaches; time correlation by encoding amplitude variations in continuously transmitted laser energy (continuous wave, CW) or measurement of the interval between a short-duration transmitted pulse and detection of the reflected return signal ('time-of-flight'). The latter is the most common approach and is the focus here. By combining a range measurement with a system for accurate instrument position and laser pointing determination the three-dimensional location of reflecting surfaces can be determined and registered to a geographic reference frame.

For time-of-flight ranging several detection methods are used to characterize the return signal (Harding, 2011). 'Full-waveform' LiDARs (FWL) digitize the entire time-varying amplitude of the return signal to measure the height distribution of reflecting surfaces illuminated within the laser footprint. 'Discrete-return' LIDAR (DRL) identifies and retains the ranges at which the energy signal exceeds a threshold. Early DRL systems typically recorded the initial ('first-return') and, if present, final ('last return') ranges above the threshold. More recent systems can record as many as 5 ranges per emitted laser pulse. Discrete returns from many pulses produce a 'point cloud' that depicts the spatial organization of reflecting surfaces. Some systems also record the received energy associated with each discrete return. Most recently photon counting LiDARs have been developed using rapid firing of low energy 'micro-pulses' and detection of the arrival time of single or a few photons for each pulse, from which single photon point clouds can be

produced. For DRL and photon counting point clouds, the data can be represented as a vertical frequency distribution (or histogram), which is analogous (though not equivalent) to a waveform.

In addition to the ranging method, LIDAR deployments may be classed on several other main criteria: the type of platform, the pointing geometry, the laser pulse repetition rate and the footprint size. Based on these criteria, there are three primary deployment types: 1.) terrestrial laser scanning (TLS), 2.) airborne laser scanning (ALS), and, 3.) portable canopy LiDAR (PCL).

TLS systems typically operate at short range (meters to 100's of m) using discrete return ranging and operating at up to several hundred kHz with very small, cm-scale footprints. Their primary use is detailed, point cloud representations of near-field targets. Some recent TLS systems also record full waveforms. TLS provides a full 3-D representation of canopy structure. The instrument is generally stationary and is fixed on a survey tripod about 1.5 m above ground. A first dimension is resolved by a rotating mirror directing the laser pulses in the vertical plane. A second dimension is resolved by the horizontal rotation of the instrument. And the third from the distance to targets derived from the laser time of flight.

ALS systems are deployed on fixed or rotary wing aircraft most commonly at low altitudes of 0.5 to 2 km using 'small footprint' (0.1−3 m) systems, with FWL, DRL and PCL variants. Several FWL 'large footprint' (10 to 30 m) systems operating at higher altitudes up to 20 km have also been developed. Scanning mechanisms of various types are used to distribute the laser pulse footprints across a swath in the flight direction, with widths of hundreds of meters at low altitude to several km at high altitude. ALS provides a full 3-D representation of canopy structure. The aircraft's movement forward provides the first dimension. While the plane moves forward a scanning mechanism (e.g., rotating or oscillating mirror) transmits pulses in a scan pattern across the swath, providing the second dimension. Swath widths are controlled by scanner field of view and typically range from hundreds of meters from low altitudes to several km from high altitudes. As with TLS, the third dimension is from the distance to.

PCL systems record the range to targets along profiles as they are carried by an operator, most often pointing the laser beam upward. The systems use relatively low cost, non-scanning laser range finders. The resulting measurements can be considered as 2-D+. One dimension is resolved by the operator walking along a transect producing forward travel of the instrument. A second dimensions, typically directly overhead, is obtained by the range to targets derived from the rangefinder. And an additional, partly resolved third dimension, is obtained by the transect pattern, e.g., parallel linear transects with their separation governed by the desired coverage and resolution.

Other LiDAR systems include the mobile LiDAR (mounted on a ground vehicle) and the autonomous terrestrial LiDAR which can be installed on a flux tower (Eitel et al., 2013). The mobile LiDAR system is mounted on a vehicle such as an all-terrain vehicle (ATV). This system can provide high resolution data, but requires that the site be accessible to the vehicle. The autonomous LiDAR uses a similar LiDAR sensor to the PCL LiDAR, but instead of being carried by a user while walking along transects, it is mounted on a pan-tilt unit which can be fixed on a flux tower. This low cost system (about 12,000 USD) allows for a scanning of part of the tower footprint at regular time intervals. Although this system has potential for monitoring purposes at flux sites, the accuracy and usefulness of the derived products in field conditions are not yet well determined.

For all the measurement approaches, upon interception of the laser pulse energy by objects, the energy is scattered in multiple directions, and a fraction is scattered in the direction of the LiDAR instrument's receiver field-of-view (FOV). The amplitude of the returned signal depends on the transmitted pulse energy, the atmosphere transmission, the distance to the target, the reflectance of the target (specifically the retro-reflectance at 0° phase angle commonly referred to as the hot spot), and the receiver aperture and throughput. The farther the instrument is from the targets being measured the more power needs to be emitted so that enough energy for object detection is reflected back towards the instrument. The received energy decreases proportional with distance squared because the solid angle

formed by the receiving mirror field of view is reduced. In addition absorption and scattering by atmospheric constituents decreases the received energy by twice the distance to the target, by an amount governed by the atmosphere optical depth.

Because of the high spatial coherence of the laser pulses (i.e., collimation) the power (energy integrated over time) can result in radiation emissions that are not eye safe. An increase in power generally translates into an increase in transmit beam size to reduce the power density within the beam. This is especially true for terrestrial systems where observers can move closer to the instrument while it is in operation. Whereas most LiDARs operate in the near-infrared, some operate at visible wavelengths where eye-safety is of greater concern.

5. Scale as a dominant characteristic of LiDAR systems

Resolution

The level of canopy structure detail which can be resolved from LiDAR measurements is directly dependent on the size of the laser footprint and the separation between footprints. The footprint size is defined by the diameter of the pulse at a given distance from the instrument and is controlled by two variables: (1) the size of the pulse upon exiting the instrument, and (2) the divergence of the pulse. The divergence angle determines how the pulse size increases with distance – typical values are 0.3 to 10 milliradians. Hence, for ALS the footprint size will increase as the aircraft flies at higher altitudes above the ground, and for TLS and PCL as the laser pulses travel farther through the canopy. Typical laser footprint sizes are 0.01 – 0.2 m at 20 m for static terrestrial LiDAR, 0.2 – 1.0 m for discrete return airborne LiDAR, 0.5 – 30 m for full-waveform airborne LiDAR, and 50 – 100 m for spaceflight LiDAR.

In order to approach or achieve complete coverage of an area, the distance between consecutive pulses (spatial resolution) needs to be close to the footprint size. Distances between consecutive pulses larger than the footprint would result in areas not being illuminated. The distance between consecutive pulses increases with distance from the instrument. In the case of static terrestrial LiDAR, it is controlled by the step angle between the directions of consecutive pulses. This greatly influences static terrestrial LiDAR coverage, since plants parts are typically located anywhere between 3 and 30 m from the instrument.

For airborne systems the footprint spacing is governed by the altitude above ground, the aircraft velocity, the pulse repetition rate, and the angular rate and field of view of the scanning mechanism used to distribute the footprints across a swath, and the steepness of the underlying topography. Most discrete return systems are used for high-resolution topographic mapping and characterization of canopy structure at sub-crown spatial scales, and so use small footprints, high pulse rates (up to several hundred kHz) and relatively narrow swaths flown at low altitudes (several km). The objective of waveform systems is typically to capture the full height distribution of all illuminated surfaces at tree crown or larger scales so use a larger footprint size, enabling lower pulse rates, wider swaths and higher altitudes (10 to 20 km) while still retaining adjacent footprints.

Occlusion

The representation of canopy structure yielded by LiDAR systems is necessarily incomplete, and the terms ‘full 3-D representation’ and ‘resolution’ used above needs to be reframed to consider occlusion. The term occlusion here refers to the fact that the laser pulses are blocked, at least partially, by leaves and branches occurring earlier along the pulse travel path, preventing interception of the pulses by material located further along the travel path (Harding et al., 2001). If occlusion reduces the energy of pulses traveling into areas of the canopy too much, then little or no information will be retrieved from these areas. The amount of occlusion depends on the footprint size, the plant area density (foliage and woody material combined, and their size distribution) and the scanning geometry. The location of occlusion is strongly dependant on system pointing direction, i.e., downward from above the canopy or from below looking up. When

comparing the typical footprint sizes for airborne instruments with the sizes of tree parts, one can see that the energy from a laser pulse will usually be only partly intercepted by plant parts located in the upper layers. The non-intercepted energy will travel further into the canopy and may be intercepted by material located further along its path. A large fraction of TLS and PCL pulses can be fully intercepted, especially in the near range, because of their smaller footprint diameter at short distances.

In the case of Airborne LiDAR systems, laser pulses are emitted at varying scan angles based on the directionality of a rotating mirror. Scan angles vary between 0° and ± 30° (depending on the system and setting used). Therefore, airborne LIDAR 'looks' at the canopy from above, and at varying angles (e.g. broader angles increase the path length, enabling pulses to reflect off of the side of trees rather than directly from crown apices). Depending on the density of trees and scan angle used, laser returns may be focused to a greater extent within canopies (broader angles) vs. from the ground surface (narrower angles). Airborne systems also have multi-return functionality, unlike many TLS sensors, and occlusion will increase with greater or lesser amounts depending on the increasing depth of penetration into the canopy, path length and foliage amount. It is important to note that the ability to penetrate the vegetation is greatly influenced by the selected pulse frequency rate (PRF), because higher PRF generally results in single pulse having less energy (Gatziolis and Andersen, 2008). Higher PRF generally also result in longer laser pulses (the duration of each laser emission), which reduces the ability of the system to resolve different objects in the vertical direction.

PCL instruments generally 'look' from below upward into the canopy so occlusion will increase with increasing height. In that sense, the combination of both can be complementary, especially in dense canopies (Harding et al, 2001). TLS instruments usually observe the full hemisphere by scanning so occlusion increases with distance travelled in all directions.

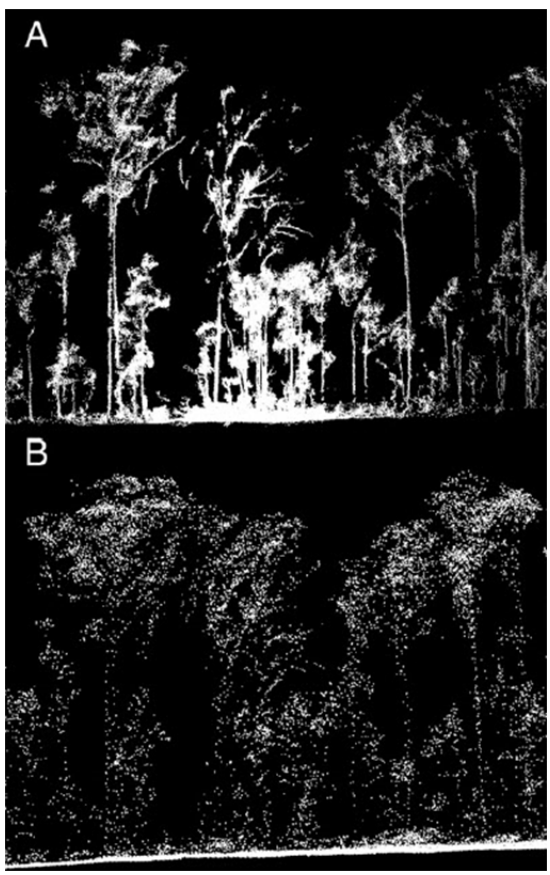


Figure 2: Difference in top of canopy and within canopy level of detail provided by TLS (A) and ALS (B) LiDAR systems (from Hopkinson et al. (2013)). The top of the canopy is better described by the ALS system, while the internal structure is better described by the TLS system.

Coverage

Discrete return airborne LiDAR can typically cover up to 1000 km^2 during a flight, depending on the instrument and platform characteristics, the flight pattern and desired footprint density. Large footprint waveform systems can cover areas up to about 10 times larger per flight. The area covered by TLS is dependent on (1) the number of scanning locations required to obtain multiple views of a site, (2) the density of the canopy (determining the level of occlusion), and (3) the level of occlusion which is deemed acceptable towards achieving the aim of the survey. Multiple directions of scanning into or out of a central location will improve issues of occlusion, and multiple plots (similar to mensuration plots) may be initiated. TLS is generally considered a 'plot level' instrument, although as research groups develop their expertise and instruments get faster, the maximum area covered by TLS is increasing. A group from the UK recently conducted TLS surveys covering 6 hectares in a European deciduous forest; the survey was performed by two people over 11 days of field work. The 6 hectares were surveyed using 352 scans from 176 locations (the instrument was positioned on grid points distanced by about 20m). The area covered with Portable Canopy LiDAR depends on the length of time the operator is walking and the level of difficulty in walking due to the terrain, or understory obstacles. The areas covered can typically extend to several hectares.

6. LiDAR research at flux sites

Canopy structure information at various resolutions and scales can be useful at AmeriFlux sites. First, describing local conditions for the purpose of comparing sites based on canopy characteristics such as tree height and crown cover. Second, those canopy characteristics which have a direct relation to energy, carbon, and water balances, such as aerodynamics properties, albedo, LAI, biomass, and the spatial distribution of leaf material. Third, the spatial variation in canopy structural properties and its relations to ecosystem dynamics. And fourth, those canopy properties which are relevant to the up-scaling of fluxes from the landscape to the global scale.

Canopy structural heterogeneity has many components and can be a complex property to quantify, and different study objectives require different operational representations of canopy structure (Parker, 1995). For example, spatial heterogeneity may be described at the scale of >50m for modeling the effect of surface roughness on cloud formation (Khanna and Medvigy, 2014), 1-10 m for modeling forest resilience to fire (Larson and Churchill, 2012), 0.5-1 m for modeling canopy roughness effects on fluxes (Hardiman et al., 2011; Hardiman et al., 2013; Parker and Russ, 2004; Paul-Limoges et al., 2013), and 0.1-0.3 m for modeling canopy gaps and light interception (Béland et al., in preparation). Because LiDAR systems widely range in scale, they have great potential for identifying and characterising structural patterns that drive scale emergent processes at the ecosystem level.

Canopy structure is often described using mean conditions (e.g., LAI, tree height), without explicit consideration of variation (Larson and Churchill, 2012; Parker, 1995). By doing so global patterns are recognised while local patterns are missed, and an important remaining advance is to develop operationally meaningful representations of this variability at the appropriate scales (Larson and Churchill, 2012). Research questions addressed at AmeriFlux sites should determine the type of LiDAR data to be used to provide information on mean attributes and their variation at the proper scale.

To date, one factor has been determinant in the use of LiDAR measurements within scientific research relating to forest canopies: the complexity of acquiring and pre-processing static terrestrial LiDAR data relative to airborne LiDAR from a user's perspective, and the spatial coverage of these systems and whether or not plot level or stand level information is deemed required. One can argue that the current predominant use of airborne LiDAR is not always based on a match between the requirements of specific scientific questions and its qualities in terms of scale and explicitness, but on access to ALS data which has been relatively simplified by two main factors: (1) airborne LiDAR surveys are typically performed by companies or organisations (e.g., NCALM) contracted to provide a service and are not directly

conducted by researchers, while this type of service is very rarely used for static terrestrial LiDAR measurements in forest environments, and (2) algorithms needed to derive the relevant products are more readily available for ALS than for TLS.

In the case of static terrestrial LiDAR, unlike ALS, acquisition is usually performed by research groups and their processing and analysis methods are less standardised with many groups using in-house developed algorithms. The most challenging aspects of static terrestrial LiDAR measurements relate to field methods and data processing: (1) combining scans acquired by positioning the instrument at multiple locations into a common spatial reference system requires rigorously controlled field survey methods, (2) minimizing occlusions requires an efficient field survey protocol, (3) processing data to account for the decrease in spatial resolution with distance from the instrument caused by pulse divergence and beam angular separation is not mature, and (4) accounting for a given volume within the canopy being explored by pulses emitted from different directions and locations is computationally challenging.

Regardless of the complexity related to static terrestrial LiDAR, it must be emphasised that airborne LiDAR has limits in providing information for a number of science questions, that scientists are best positioned to appreciate this issue, and that if they have access to higher level of detail in structural representations they may be able to better address specific scaling issues. It is also important to note that expertise on TLS field methods in forests is quickly being developed; this results in increased coverage (up to about 6 ha in 11 field days as mentioned above) and better quality data in terms of occlusion and accuracy. Processing algorithms are also being developed by various groups for TLS data acquired in forests. For that reason, we recommend that static terrestrial LiDAR and portable canopy LiDAR derived products be made available concomitantly with airborne LiDAR products at AmeriFlux sites.

PCL surveys have similar benefits to ALS in terms of straightforward data collection and processing. In addition the surveys can be more appropriately designed for specific ecosystem objectives within the limits of practical coverage and the 2D+ character of the observations. The number of PCL systems currently in use is limited, but they are easily replicated at low cost.

Most of the current research using canopy structure information at AmeriFlux sites can be grouped into three components: (1) the interpretation and modeling of carbon, water and energy fluxes, (2) an ecosystem dynamics component, and (3) the process of up-scaling local observations to regional patterns. Some examples of recent research in those areas are given below, and a more exhaustive list of published studies is given in Table 3.

Interpretation and modeling of carbon, water and energy fluxes

Canopy structure has a significant role in processes driving photosynthesis, evaporation, respiration and surface albedo. Here the main scale of interest is the flux tower footprint, but, as is the case for each flux, the processes involved require resolution of patterns at much finer scales. Terrestrial LiDAR may thus be best suited for this type of application, including those studies addressing changes in canopy structure due to disturbance. This is because the amplitude of the change in structure is likely to be significantly larger than the uncertainty in the products derived, which may not be the case when using ALS data.

Kobayashi et al. (2012) used a map of individual tree position and crown dimensions obtained from discrete airborne LiDAR to demonstrate the gain in considering 3D effects in radiative transfer modeling in terms of impact on water and carbon flux modelling. Hardiman et al. (2011) linked primary productivity and an index of complexity derived from portable canopy LiDAR (PCL) data; they looked at total LAI and an index of rugosity as factors. Stark et al. (2012) investigated links between structure (leaf area and light availability) and forest growth. Mitchell et al. (2012) used LiDAR to couple spatial changes in forest structure and variation in evapotranspiration. Emanuel et al. (2011) described the vegetation and topography structure within a tower footprint and showed that the cumulative growing season NEP is highly heterogeneous for complex landscapes. Stoy et al. (2013) emphasizes the role of structural

heterogeneity in the energy balance closure problem at FLUXNET sites, but did not use LiDAR data. Maurer et al. (2013) and Paul-Limoges et al. (2013) used airborne LiDAR to derive canopy surface roughness parameters of flux sites. LiDAR may also help the implementation of such popular models as MAESTRA (Medlyn, 2004) and RATP (Sinoquet et al., 2001). High resolution explicit physical modeling of water and momentum transport in the canopy can use LiDAR to describe explicit canopy domains. This was used for example in meter-scale hydrology models (He et al., 2014), canopy air large eddy simulations (Maurer et al., 2014), and tree-branch-level hydrodynamics (Bittner et al., 2012). Ongoing work is demonstrating the use of temporal ALS over FLUXNET sites in Canada and Australia to support growth monitoring and the integration of ALS-based canopy biomass change with flux tower estimates of NEP (Hopkinson, 2012). Multi-temporal TLS may also be used to monitor growth and mortality, which are crucial to ecosystem modeling.

Ecosystem dynamics

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. The scale at which simulations can be made depends on the choice of the model and the initial conditions. 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. 'Big-Leaf' models like JULES (Best et al., 2011; Clark et al., 2011), CLM (Levis et al., 2004; Oleson et al., 2008) and IBIS (Foley et al., 1996; Kucharik et al., 2000) essentially map properties of a whole canopy onto a single representative leaf – or is discretized into a multi-layer approach vertically divided the canopy into equivalent leaf area increments. These models are less computationally expensive, and so are regularly used for continental to global scale prognosis.

Above-ground forest structure and composition is a key determinant of the current and future biophysical and biogeochemical functioning of terrestrial ecosystems, including their carbon balance, and the exchange of water and energy between the land-surface and the atmosphere. Information on these attributes has traditionally come from ground-based inventories of the plant canopy within small sample plots. Remote sensing, and specifically on airborne platforms, can provide spatially consistent information on the land surface at larger scales, and has been used to test, validate or constrain output from ecosystem models. Airborne radar-derived structure has been used to initialize biomass in ecosystem models such as Zelig (Ranson et al., 2001) and the Sheffield Dynamic Global Vegetation Model (Le Toan et al., 2004) mostly as a diagnostic tool to determine where land use history was accurately represented. Airborne LiDAR-derived structure has been used to parameterise canopy photosynthesis models (e.g. (Chasmer et al., 2011; Kotchenova et al., 2004; Yang et al., 2010) to improve estimates of carbon fluxes at the scale of the flux tower. Patenaude et al. (2008) used three sources of remote sensing: radar data on biomass, LiDAR data on tree height, and hyperspectral data on LAI, to aid in parameterizing nondynamic variables in the 3-PG model.

The Ecosystem Demography model (ED2) is a particularly powerful ecosystem model as it 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. Building on the earlier work of Hurtt et al. (2004), Antonarakis et al. (2011) compared ED2 biosphere-model simulations for the La Selva tropical forest ecosystem initialized with Radar and LiDAR measurements against ED2 simulations initialized with potential vegetation, and against ED2 simulations initialized from forest-inventory measurements of vegetation structure and composition. This study showed that single attribute LiDAR and radar-derived height and biomass, less adequately constrains terrestrial biosphere models than fine-scale (individual tree information) ecosystem information. A subsequent study by Antonarakis et al. (2014) at Harvard Forest, Massachusetts, revealed that a combination of airborne LiDAR and hyperspectral measurements can be successfully used to measure fine-scale forest structure and composition of a forest

to constrain biosphere model predictions of terrestrial carbon fluxes around the flux-tower footprints (net carbon flux error reduction from 85-104% to 37-57%).

Big-leaf models such as JULES which aggregates vegetation structure and composition at vertical height layers are an important future avenue when incorporating LiDAR data. The multi-layer scale is of particular interest, as this is a direct connection to remotely sensed vertical foliage, and these types of models have a better supported connection to other components of global circulation models, making up-scaling the model-LiDAR fusion to regions or the globe more tangible. This may imply that regional to global scale model predictions could make use of satellite LiDAR data (e.g. ICESat, ICESat-2, GEDI).

Up-scaling

Large scale information about ecosystem structure and function, as well as the dynamics therein, are needed for monitoring and predicting changes in the Earth system. Passive optical remote sensing is an essential tool to that end, and how representative those observations are of relevant descriptions of surface parameters is critical. The scale of interest is the image pixel scale, typically 0.5-1 km in side length. Airborne observations are thus best suited for this application, as well as future satellite based missions like the GEDI LiDAR.

Ryu et al. (2011) created a model using MODIS data to map GPP and evapotranspiration at global scale. Data from FLUXNET sites was used to validate the results. Canopy structure is addressed using the clumping map of Chen et al. (2005). This map is increasingly being used, but may need further validation. LiDAR data of appropriate resolution and scale would contribute to that validation. Chasmer et al. (2011) used a number of metrics from discrete return airborne LiDAR 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. Recently, Knyazikhin et al. (2013) stressed the need to consider the role of canopy structure when retrieving leaf nitrogen from passive optical remote sensing. They used a radiative transfer model to support that conclusion. The use of such models is increasing, in part because detailed descriptions of canopy structure are increasingly made available, and LiDAR has an important role to play in providing these. Research groups running these models, as well as the radiation transfer model intercomparison (RAMI) community exercise (Widlowski et al., 2013) are potential users of AmeriFlux sites for validating and calibrating models and algorithms.

Table 3 : **Additional applications and studies**

Application	Summary	Reference
Interpretation and modeling of carbon, water and energy fluxes	Modelling of GPP based on light response curves and scaling to MODIS	Chasmer et al. (2009)
	Changes in growth and CO2/water exchanges during drought/non-drought conditions	Petrone et al. (2014)
	Influence of climate on CO2 and water fluxes, comparisons with canopy structure	van Gorsel et al. (2013)
	Night-time sap flow. LiDAR used to determine tree height variability	Fisher et al. (2007)
	Review of plant responses to stress and variations in structure	Omasa et al. (2007)
Scaling	Assessing MODIS land cover accuracy within mixed pixels, sensitivity of NPP/GPP to structure	Cook et al. (2009)

	Comparing FPAR from MODIS vs. within pixel heterogeneity using lidar-based model	Chasmer et al. (2008)
Canopy roughness influences on fluxes	Comparing with tree height derived from Surface-Layer	Pennypacker and Baldocchi (2015)
	LIDAR and SPOT data used to parameterise zero plane displacement and roughness length models	Tian et al. (2011)
Average site conditions and heterogeneity	Literature review on understanding C cycling, use of LiDAR is discussed.	Canadell et al. (2004)
	Review of recent research on Pacific Northwest Forests.	Bond and Franklin (2002); Emanuel et al. (2011)
Light use efficiency and photochemical reflectance index	Used lidar-structure model to determine shadow fractions for light use efficiency and PRI assessment	Hall et al. (2008)
	Examining light use efficiency from space using lidar shadow fractions and PRI	Hilker et al. (2011)
Topographic influences on CO2 and water fluxes	Soil respiration variability based on topographic position.	Riveros-Iregui et al. (2012)
	Influence of topography and soil moisture on soil respiration in permafrost, fen, bog land cover types	Chasmer et al. (2012)
	Influence of ground morphology and soil moisture fluxes on respiration	Riveros-Iregui et al. (2011)
Biomass	Comparison of NPP using eddy covariance with allometric and LIDAR-based measurements of growth	Hopkinson et al. (In review)
	Estimating above ground forest C stocks using lidar within a flux footprint	Ferster et al. (2011)
	Used ECHIDNA TLS to determine biomass and other structural attributes	Yao et al. (2011)
Leaf physiology	Chlorophyll content	Eitel et al. (2010)
	Moisture content	Gaulton et al. (2013)
	Non-photochemical quenching	Magney et al. (2014)
Influence of canopy structure on CO2 and water fluxes using footprint model	Influences of structure and topography within footprints surrounding an eddy covariance system	Chasmer et al. (2008)
	Structure influences on water fluxes in mixed land cover types, comparison with eddy covariance.	Sutherland et al. (2014)
	Examined representation of CO2 fluxes based on vegetation structure	Barcza et al. (2009)
Vegetation structure, single trees	Detection of tree-tops from airborne lidar data via watershed segmentation and local maxima.	Chen et al. (2006)
	Basal area and stem volume estimated for single trees using airborne lidar data	Chen et al. (2007)
	Determined tree stem diameters using TLS	Lovell et al. (2011)

7. LiDAR data acquisition and processing

Airborne LiDAR (ALS)

The cost of an airborne LiDAR acquisition is typically about USD 20,000 and is highly dependent on area location. A twin otter plane and the associated crew will cost somewhere on the order of $4,000 / hour before any data processing. Thus, prices are low per unit area if you have a lot of area to cover but if sites are small and isolated, costs could be a lot higher. It may be that NEON, NASA or NCALM can give AmeriFlux favourable rates if sites are coincident with their own objectives.

Researches at NASA Goddard Space Flight Center operate several systems for canopy structure measurements: G-LiHT (Cook et al., 2013), a small footprint, discrete return system, which includes hyperspectral and thermal imaging instruments; LVIS (Blair et al., 1999), a large footprint full-waveform system; and SIMPL (Harding et al., 2011) and MABEL (McGill et al., 2013), photon-counting systems.

The specifications of the NEON AOP instrument are not fixed at this time, but will incorporate an hyperspectral imager and will record full waveforms. The NCALM system records full-waveform and uses a dual beam divergence (concomitant small and large footprint).

One important characteristic of airborne LiDAR measurements is often not considered in the computation of metrics: the angle of incidence of the pulse, which is inevitable because of the lateral scanning pattern and is variable between measurements (see Figure 3), and can be as much as 25-30 degrees. The maximum incidence angle allowed is a parameter which can be decided upon will planning the survey. Scan angle can create a significant bias; this can be easily mitigated by flying 50% overlap and should be standard for AmeriFlux sites. Researchers are now emphasising the need to require the data provider to include the angle of incident of the pulse which generated each 3-D point within the metadata.

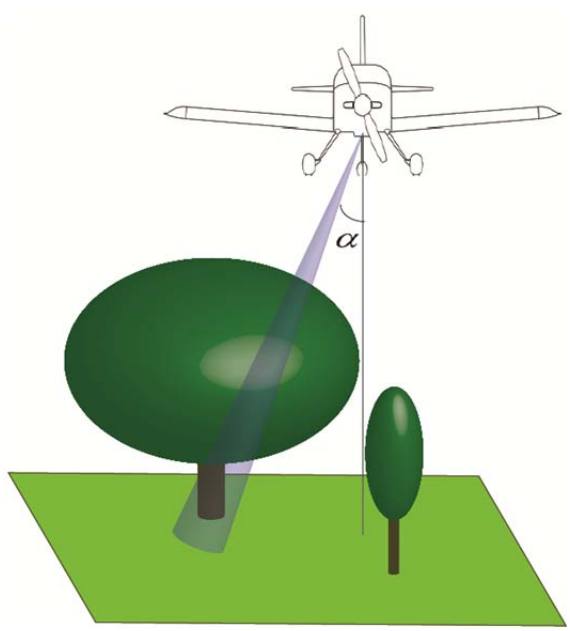


Figure 3: Illustration of an angle in the incident laser pulse emitted from an airborne platform

Discrete return at high enough resolution can provide reliable estimates of crown cover. Larger footprint waveform LiDAR is better for foliage cover. The new hybrid systems should offer the capability to do both. Full-waveform data is rich in information but physically-based processing methods for their interpretation are still lacking. Most often

simple metrics are being used based on empirically established relationships by correlation with field plot data. It is important to note that most ALS products require calibration from ground plots if high confidence and comparable datasets is sought. A plot calibration approach can be realized through a LiDAR multiscale design strategy, where plots are measured using TLS. More detail on this strategy is provided in the next section. The products provided by the ALS are described in **Table 4**, and a cost-benefit analysis for the ALS, TLS and PCL systems is presented in Table 5.

Static terrestrial LiDAR (TLS)

Static terrestrial LiDAR instruments cost between 40,000$ and 200,000$ including a range of optional features. Riegl current makes the only commercially available system with full-waveform capability. This capability has potential in forest environments, but has not yet been fully explored. Some TLS systems are being developed in-house, e.g., the EVI and DWEL (CSIRO and Boston University) and the SALCA (University of Salford, UK), but these experimental systems currently suffer from long scanning times, reducing their potential for use in operational contexts. The main features to look for in a TLS for use in forest are (1) wavelength, (2) beam size, (3) angular resolution, (4) pulse and scan rates, and (5) features fostering efficient co-registration of scans acquired from different positions. The instrument wavelength will determine the possibility of separating leaves from wood in the data on the basis of return intensities. Beam size is critical when retrieving leaf area density because estimates are based on gap fraction, and larger laser beams sizes may underestimate gap fraction. The angular resolution determines the minimum distance between consecutive points at a given distance from the instrument; most current systems have high enough resolution. Instrument pulse and scan rates are important since high rates can significantly reduce field time and/or increase the number of measurements per day. It should be noted that some commercially available TLS instruments at the lower end of the cost bracket given above (about 40,000$) operate continuous wave lasers which greatly limit the maximum range of the instrument and increases the amount of noise in the data.

To cover the area while minimizing occlusions requires a carefully planned set of measurements from different locations within the canopy. Current methods make use of reference reflectors strategically placed in the forest which should be visible from the different measurement locations. These references are used as tie points to transform the x,y,z coordinates of each point cloud from independent spatial reference systems to a common reference system. This process is critical for providing accurate results. The different fabricants have developed various ways of making the use of reference reflectors to facilitate co-registering data from different locations in a common reference system. Some of them have become quite efficient by enabling automatic searching of the targets.

In order to assess the potential for multiple-wavelength LiDAR characterization of vegetation characteristics, including differentiation of foliage and woody surfaces, experimental terrestrial scanning systems have been developed. DWEL (Douglas et al., 2012) and SALCA (Gaulton et al., 2010) operate at two near-infrared wavelengths, and a laboratory prototype (Hakala et al., 2012) operates at eight wavelengths spanning visible to near-infrared.

An important consideration when processing static terrestrial LiDAR data is the decrease in pulse density per unit area with distance from the instrument. One meter away, the pulses may be separated by less than a millimetre, and as they travel forward they diverge from one another. When estimating the density of plant material based on the number of pulse making contact it is critical to account for this effect. Ray-tracing algorithms can be used to derive useful statistics from the LiDAR point cloud; these algorithms are complex and not commercially available. They are generally developed by individual research labs for their own use. Béland et al. (2014) recently made available such model which uses computational geometry. Some of the methods used to derive products from TLS require further research, for example, deriving leaf area for needle leaves. Methods to derive accurate estimates of biomass are also becoming available. The availability of such methods is key in making use of TLS data at flux sites.

The recent availability of such methods to derive biomass and the 3-D distribution of foliage from TLS measurements offers new possibilities for answering research questions requiring fine scale canopy structure information like light

interception dynamics, carbon allocation to growth, and ecosystem responses to disturbances. TLS measurements can also enable a better calibration/validation of products derived from airborne systems through a LiDAR multiscale design strategy (Figure 4). This requires careful attention to tying the TLS survey to a global coordinate system using survey grade GPS stations.

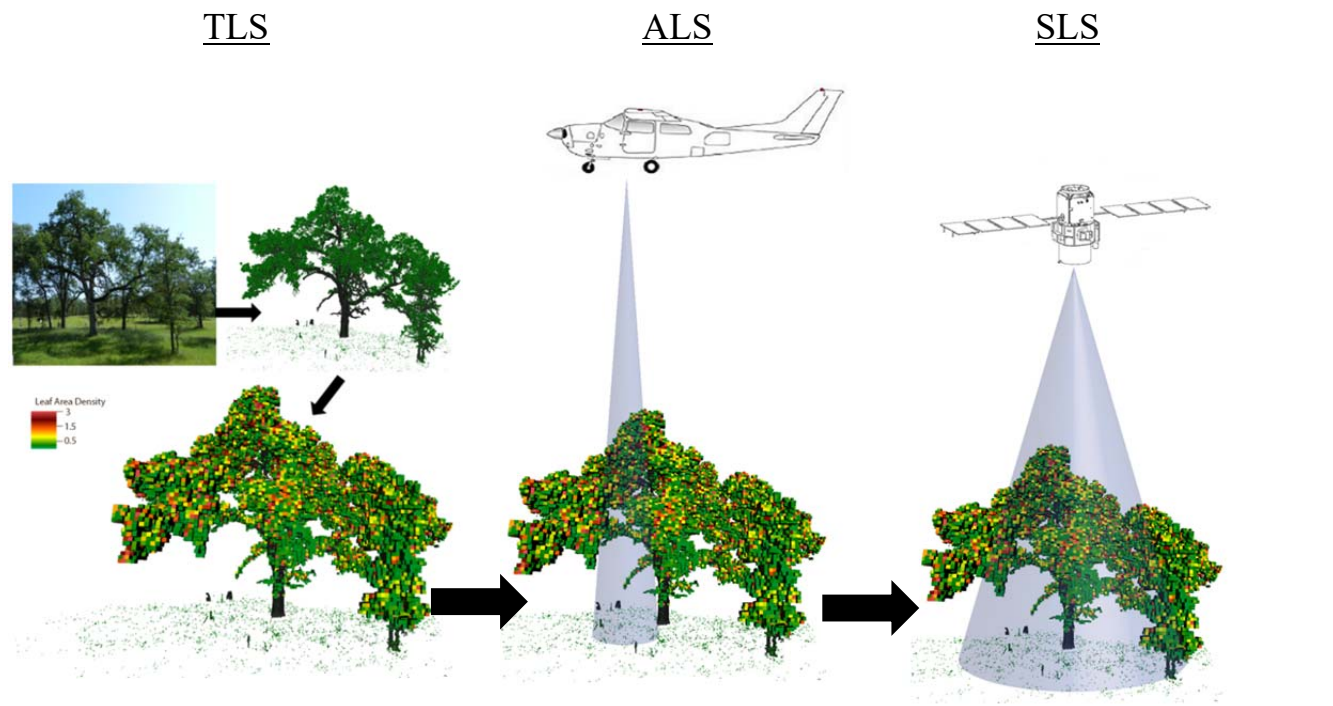


Figure 4 : A LiDAR multiscale design strategy allowing the calibration and validation of products derived from airborne and spaceflight LiDAR products

Portable canopy LiDAR

The Portable Canopy LiDAR (Parker et al., 2004) system represents a compromise between complexity, the level of detail provided, and the area covered. While the static terrestrial LiDAR will necessarily require skilled users trained for operating the instrument in forested environments, the portable canopy LiDAR requires little training and processing methods are much simpler relative to static terrestrial LiDAR.

Training a person to operate the PCL is simple, so it can be sent on site without an operator to acquire data at a higher temporal repetition with a lower cost. There lies its main advantage over other systems: cost of acquisition, ease of operation, and possible repeatability of measurements. The latter is an advantage for assessing the effects of events like droughts, storms and major disturbances.

The PCL is carried along the forest floor while the upward-looking laser rangefinder records distances to overhead targets at a high-frequency. The sampling can be organized and accomplished in a matter of hours. Data processing is similarly rapid, using software supplied by the development team. An estimate of the vertical distribution of surface area density (m^2m^{-3}) in narrow horizontal bins is a primary result. Combined over a sampling transect such estimates may be depicted as a horizontal section of canopy surfaces – this representation shares several similarities with the CAT-scans (Computerized Axial Tomography) used in medical imaging. When collected over horizontal samples one may show the mean vertical distribution of canopy surface, the Canopy Height Profile (CHP), and its spatial variation. Horizontal samples can also be collected along parallel transects with a separation distance of 1-5 m between transects, which allow producing a 3D, volume-filling aggregate dataset of the canopy structure over an area of up to 05 ha, limited by the time an operator can spend within a single sampling period.

A variety of specific measures may also be extracted: the height of the canopy (useful for estimates of biomass and carbon), the texture of the canopy surface (useful in studies of atmospheric-surface exchanges) and the internal complexity of the forest (useful for assessments of habitat and biodiversity). Specific metrics derived using the PCL include: 1) the LOCH (Local Outer Canopy Height): the distance from the ground to the highest vegetation surface overhead - the rugosity is its standard deviation, 2) the gap fraction: proportion of zenith observations with sky, and 3) the porosity: the percentage of unoccupied voxels below the undulating canopy surface – the total porosity is similarly percentage openness below the surface defined by the highest point.

Table 4: Products derived by each LiDAR system. Numbers refer to 1: experimental, requires more research, 2: operational but accuracy is not well defined or controlled, 3: operational and accuracy is characterised. +/- refers to the potential to provide product at a scale and accuracy level which is relevant to research at flux sites

Retrievable metric	LIDAR Platform and Measurement Approach			
	Terrestrial Laser Scanning (TLS)	Airborne Laser Scanning (ALS)		Portable Canopy LiDAR (PCL)
		Small Footprint	Large footprint	
Ground topography	**2 -**	**3**	**3**	**No**
Canopy height	**2 +**	**3+**	**3**	**2**
Stem map	**3 +**	**2**	**No**	**1**
Crown dimensions	**3 +**	**2**	**1-**	**1**
Canopy texture	**2**	**3**	**2**	**3**
Percent cover	**2+**	**3**	**2**	**3**
Leaf area distribution	**3+**	**2**	**1**	**3**
Leaf Area Index (LAI)	**3+**	**2+**	**1**	**3**
Biomass	3+	2+	2	2
Stem density and basal area	3+	1	1	2
Foliage clumping	2+	1	1-	2
Aerodynamics parameters	2	2+	1	2

Table 5: Cost-benefits analysis. Costs are estimated for 10 sites surveyed every year for 5 years.

	ALS	TLS	PCL
Costs breakdown	Typically 4,000$ per hour through private contracting (not including data processing). Agreements with NCALM or other may lower the costs. Sites funded by NSF may benefit from reduced acquisition costs. Total cost is a function of (1) site location with regards to the plane initial location, and (2) area size to be surveyed and desired flight settings.	There are no costs for instrument if survey is done by UNAVCO. About one week per site is required for each survey. UNAVCO estimates that the costs for surveying a non NSF funded site is about 8,000$ (salaries and travel expenses). For an NSF funded site the only expense to cover are travel, which would come down to about 5,000$.	The instrument cost is about 12,000$. The instrument is simple enough to use that it can be shipped to the sites and operated by the group members. Cost of shipping the instrument is estimated at 200$ per site.
Cost for first year	Estimated at 20,000$ per site. 200,000$	10*8,000= 80,000$	12,000+10*200= 14,000$
Total cost for following years (4)	Same yearly costs as above. 800,000$	Same yearly costs as above. 320,000$	4*10*200= 8,000$
total cost after 5 years	**1,000,000$** Cost of processing data not included	**400,000$** Cost of processing data not included	**22,000$** Cost of processing data and local labour for performing the survey not included
Products provided	See **Table 4**		
Bottom line from a cost-benefit perspective	• Most advantageous when areas to survey are large, for example national forest inventories. Costs per hectare are high for flux sites.	• Need to build expertise in field methods and data processing over the long term	• Low costs offer high repeatability

UAV

NSF supported Air CTEMPs, a group within the Center for Transformative Environmental Monitoring Programs (CTEMPs), is looking to offer a UAV-based LiDAR measurement service to researchers in the USA by mid-2016. This system is expected to provide coverage in the 1 km^2 range with a higher level of detail than is currently available from ALS. This data is also expected to be less noisy than ALS data since the aircraft flies at much lower altitudes (about 300 feet).

8. Suggested LiDAR acquisition strategy

In considering LiDAR systems, it should be clear that several of the processing methods involved are at different stages of readiness, and that concerted efforts from AmeriFlux in data acquisition and sharing have the potential to promote the development of these methods to an operational level more rapidly. In considering investments for data acquisitions, there may be a need to set an orientation towards a focus on operational methods and/or on promoting methods development, perhaps through data sharing, supporting grant applications to other sources, and encouraging collaborative research between AmeriFlux sites PIs and the LiDAR community.

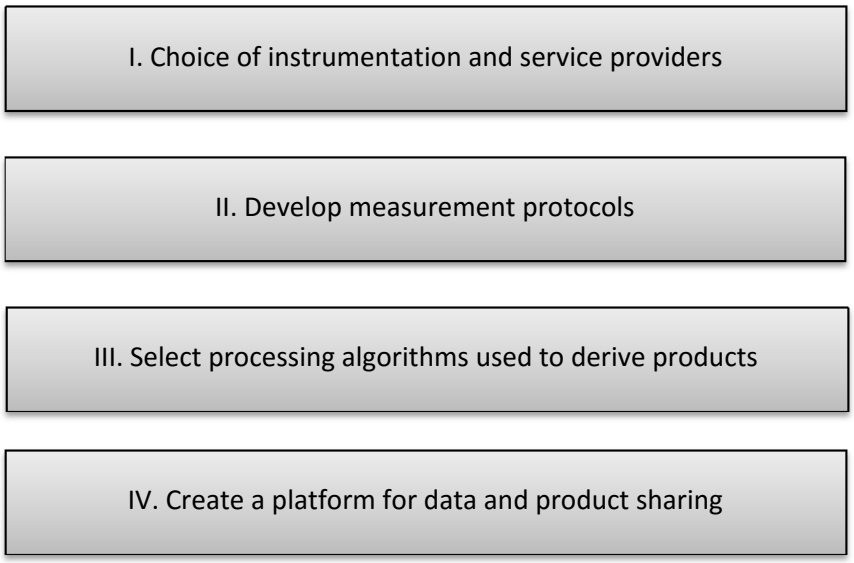
Several scientific questions require information on within canopy structure, and it is our opinion that making such information available to researchers will improve capacities for addressing ecosystem questions at appropriate scales. We thus recommend a multi-scale approach to LiDAR data acquisition over AmeriFlux sites, making use of the different currently available LiDAR systems. This approach also allows the calibration and validation of ALS products. Static terrestrial LiDAR and airborne LiDAR are complementary in many aspects (Chasmer et al., 2006; Hopkinson et al., 2013; Hosoi et al., 2010) and sites with good quality data from above and below canopy have great potential for looking at complementarity and calibration/validation of airborne products. For this reason static terrestrial LiDAR and airborne LiDAR should be acquired at the same sites and ideally at the same time. A Portable Canopy LiDAR (PCL) instrument should send to the sites at intervals to monitor structure dynamics.

A LiDAR strategy should consider the following elements: (1) the most important questions asked at the sites, and the associated requirement in terms of the level of detail for canopy structure descriptions. For example, to detect growth or change in structure, we need a system with high resolution and repeatability; (2) the need for repeat intervals; and (3) the availability of operational methods/algorithms for processing LiDAR data and derive useful products. Regarding the later point, we consider that few flux site PIs are interested in participating in the processing of LiDAR data. It is assumed that a majority will prefer having access to products along with an appreciation of the uncertainty in the derived variables. We thus recommend that AmeriFlux hire personnel dedicated to the processing of LiDAR data and provide site PIs with products instead of raw data.

UAV-based LiDAR can potentially replace ALS at flux sites by lowering long term monitoring costs and providing higher resolution data while still enabling sufficiently large area coverage. A full assessment of potential and limits of the UAV system is not currently available, but should become available in the next year, at which point a complete cost-benefits analysis should be done. It should be noted that this system is highly complex due to the navigation and inertial monitoring unit components, which are key to providing reliable data from such systems, and the need to guide the aircraft from a distance and keep all

equipment to a minimum weight. However, given recent progress in this field this type of LiDAR system is expected to become the best option for flux sites in the near future. It also allows for faster response than a full-sized ALS system which is better suited for a response system to be deployed after disturbance.

For all LiDAR acquisitions we recommend the following four components strategy:



I. Choice of instrumentation and service providers

ALS:

We recommend AmeriFlux use the services of NCALM, a research center funded by NSF to support the use of airborne laser mapping technology in the scientific community. NCALM benefits from over 10 years of experience in providing research quality ALS observations to different scientific communities. Commercial service providers will often keep some processing methods secret, for example the triggering of returns in discrete-return instruments. With full-waveform instruments efforts should be made with the service provider to record the outgoing laser power, which can be highly variable. This information is important if one is looking to interpret the intensity of the returned energy, and will be key in making use of full-waveform information.

TLS:

We recommend using the Riegl VZ-400 commercial system, which provides a range of advantages over other existing systems and is currently widely adopted. Considering the complexity of acquiring and pre-processing static terrestrial LiDAR data, we recommend that AmeriFlux use the services of UNAVCO, a non-profit university-governed consortium funded by NSF with a mandate to facilitate geoscience research and education using geodesy. UNAVCO benefits from several years of experience in TLS surveying for different research communities. They have 3 Riegl VZ-400 units along with survey teams

trained on their use. They have limited experience with making TLS measurements in forests, hence this capacity will need to be built.

II. Develop measurement protocols

ALS:

Main sensor and flight configuration parameters variations can alter the manner in which the canopy environment is sampled (e.g., altitude, pulse repetition frequency / pulse power, scan angle, flight line overlap, pulse width, scanning patterns, photon counting vs signal thresholding). Other attributes like signal intensity and its potential value for attribute mapping should be considered. It might also be worth noting environmental, terrain and other system error propagation uncertainties in the final point cloud solution and how these can impact our ability to consistently map canopy attributes. Furthermore, most ALS technology and surveys are optimised for terrain mapping and not for consistent sampling of the above ground canopy environment. We thus recommend AmeriFlux to support a working group tasked with developing clear guidelines for ALS protocol at flux sites.

TLS:

Measurements should be made in leaf-on and leaf-off conditions when possible to allow efficient separation of leaf and foliage within the TLS data, and better estimates of biomass in leaf-off conditions. Each TLS survey should be tied to a global coordinate system using survey grade GPS stations. UNAVCO has the equipment and expertise to perform this step which is critical to overlaying TLS and ALS data for comparison purposes.

AmeriFlux should work with UNAVCO to develop field measurement protocols and improve field methods as needed to allow equivalent quality surveys over all forest types, including dense and structurally complex canopies. The acquisition protocol developed should be allowed to evolve with advances in the technology. The survey should cover plots of about 50 x 50 m^2 in area, with less than 15% occluded volumes.

The deployment of a TLS survey team in response to a disturbance should be arranged to assess changes in canopy structure (both in terms of changes in foliage quantity and arrangement, and standing biomass). TLS should ideally be acquired concomitantly with ALS surveys. Repeat intervals should be determined according to site characteristics, i.e., growth rate, disturbance dynamics, and research priorities at the site.

For all LiDAR acquisitions, metadata relating to details on the acquisition should be documented in a standard form.

PCL:

As with TLS, measurements should be made in both leaf-on and leaf-off conditions. A choice between long linear transects or parallel short-transects for 3-D plots should be made. This may depend on the science question at the core of the site research and of the relevant scale of spatial heterogeneity that the measurements should capture. For tree-scale and gap-scale heterogeneity we recommend 3-D 50x50 m plots, while for larger plot scale heterogeneity, 0.5 km line transects will be preferable. With additional effort, it is possible to include both. A measured grid should be laid out in the site to allow calibrating the

locations during the PCL operator movement, and to allow repeated measurements in the same location at different seasons and years. Sites where the canopy is too dense and the canopy top is obscured in most locations should not be sampled with PCL and ALS would provide a better solution for these sites.

III. Select processing algorithms used to derive products

We recommend that AmeriFlux provide products instead of only raw data to site PIs both for ALS and TLS. NCALM and UNAVCO can provide pre-processed data, i.e., data is merged, aligned, and georeferenced, and AmeriFlux should provide the processing to deliver higher-level data products using complex models adapted to the needs of the flux community.

We suggest AmeriFlux support a benchmarking exercise of existing methods to help select specific processing methods and quantify the related uncertainty. This could be done using a virtual laboratory approach, where virtual forest representations are used as a basis to test algorithms on simulated LiDAR measurements, and determine the most appropriate algorithm for each product, e.g., tree height, biomass, leaf area distribution. Capacities to carry this exercise currently exist.

The delivered products should include the following:

<u>1-D data:</u>

- Leaf Area index (unitless), TLS, PCL
- Foliage clumping (unitless), TLS
- Biomass (t/ha), TLS, ALS
- Cover fraction (unitless), ALS, PCL
- Mean tree height (m), ALS, PCL
- Canopy roughness length (m), ALS, PCL

<u>2-D data:</u>

- Stem map with Diameter at Breast Height (DBH), TLS
- Canopy height model, ALS
- Vertical foliage density profile, TLS, ALS, PCL
- Ground elevation, ALS

<u>3-D data:</u>

- Leaf area distribution (voxels), TLS
- Wood structure (voxels or cylinders), TLS

IV. Develop a platform for data sharing

LiDAR data should be well documented with metadata. A web based database for LiDAR should be integrated to the existing AmeriFlux web database. An open source software for visualisation and basic processing of 3D data should be selected and made available from the web site.

Existing LiDAR data should be processed and integrated to the web database. Attention should be given to copyright issues. Some existing data may be of limited value where metadata is missing, or where field measurement protocols were poorly defined. Providers of ALS data usually provide sufficient metadata, although this is not always the case, especially in older surveys. Issues with metadata and field measurement protocols are significantly more frequent with TLS data.

Making such a database widely available will not only support research at individual flux sites, but also to enable cross-system comparisons. Furthermore, it provides the LiDAR research community with valuable data to improve LiDAR processing methods, in particular through the use of modeling approaches to simulate airborne and spaceflight LiDAR observations from TLS-based canopy descriptions. Such simulations could help (1) better understand the sensitivities of the existing and hypothetical LiDAR instruments to biophysical parameters, and (2) provide better estimates of the uncertainties in products derived from airborne and spaceborne systems.

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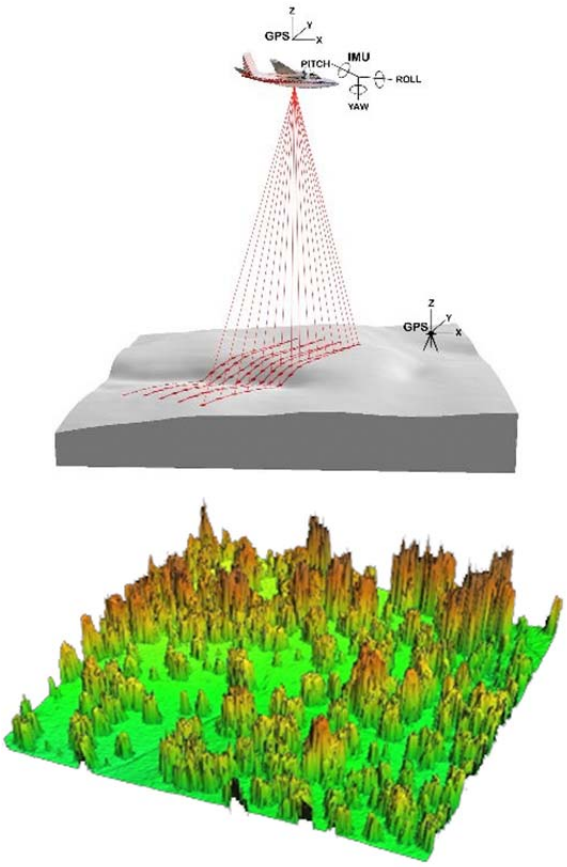
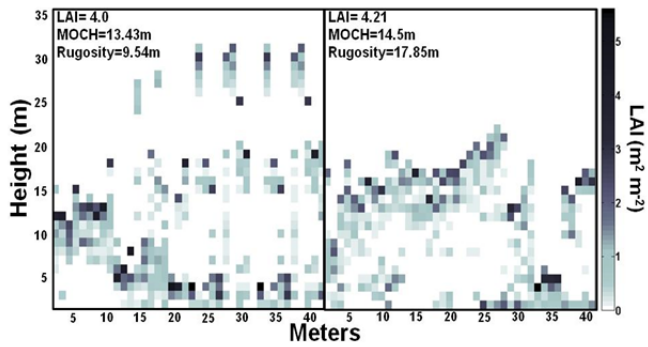
Appendix 1: **Airborne, Portable Canopy, Terrestrial, and Unstaffed Airborne LiDAR systems**



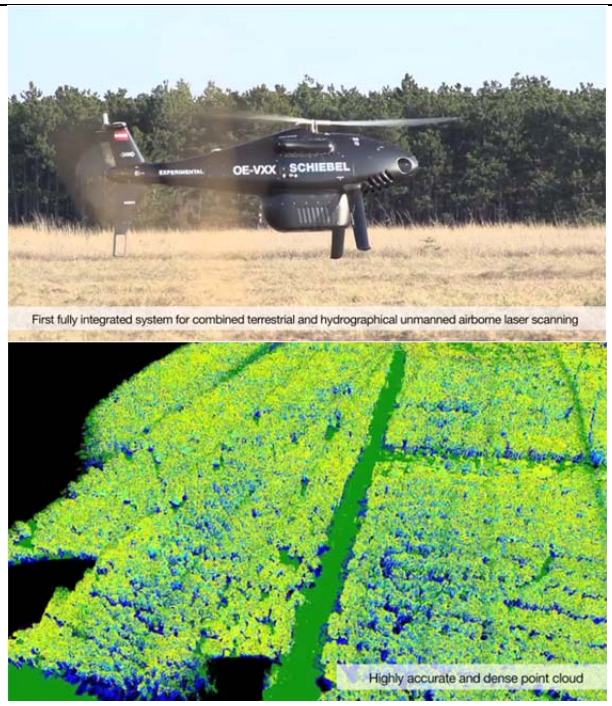
Airborne LiDAR (top image UNAVCO)



Portable Canopy LiDAR

;

Terrestrial LiDAR (top image Riegl)



UAV-based LiDAR (images Riegl)

Appendix 2: List of FLUXNET sites known to have Airborne LiDAR (ALS) data available as of September 2012. Sites with concomitant terrestrial LiDAR (TLS) data available are marked with an asterisk, and sites with Portable Canopy LiDAR (PCL) data are marked with †. Details on individual datasets is available at : http://nature.berkeley.edu/mbeland/FLUXNET_LiDAR/

Deciduous Broadleaf Forest

- Fontainebleau, France
- Oak Openings, Ohio, USA
- Silas Little Experimental Forest, New Jersey, USA*†
- Smithsonian Environmental Research Center (SERC), MD, USA†
- Willow Creek, Wisconsin, USA

Evergreen Broadleaf Forest

- Tumbarumba, Australia
- Wallaby Creek, Australia

Evergreen Needleleaf Forest

- Campbell River, B-C, Canada
- Cedar Bridge, NJ, USA*
- GLEES, Wyoming, USA
- Howland Forest, Maine, USA*
- Hyytiala, Finland*
- Lavarone, Italy
- Loobos, Netherlands*
- Metolius, Oregon, USA†
- Niwot Ridge, Colorado, USA*
- Renon/Ritten (Bolzano), Italy*
- Wind River Crane Site, Washington, USA†

Mixed Forests, Deciduous Broadleaf

- Bartlett Experimental Forest, NH, USA*
- Duke Forest, NC, USA†
- Fichtelgebirge, Germany
- Hainich, Germany
- Harvard Forest, Massachusetts, USA*†
- Laegeren, Switzerland*
- Park Falls, Wisconsin, USA

Mixed Forests, Evergreen Needleleaf

- Groundhog River, Canada*
- Loblolly Pine, NC, USA†
- Weidenbrunnen, Germany

Savannas and Shrublands

- Adelaide River, Australia
- Daly River Savanna, Australia
- Dry river, AU
- Fogg Dam, Australia
- Howard Springs, Australia
- Las Majadas del Tietar, Spain*
- Mata Seca, Brazil*
- Santa Rosa National Park, Costa Rica*
- Skukuza, South Africa*
- Tonzi Ranch, CA, USA*†

Additional sites not included in the 2012 survey:

Deciduous Broadleaf Forest

Alice Holt, UK

Evergreen Needleleaf Forest

Tharandt, Germany

Norunda, Sweden

Mixed Forests, Deciduous Broadleaf

U. Of Michigan Biological Station, USA†