Light Detection and Ranging (LIDAR): An Emerging Tool for Multiple Resource Inventory

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ABSTRACT

Airborne laser scanning of forests has been shown to provide accurate terrain models and, at the same time, estimates of multiple resource inventory variables through active sensing of three-dimensional (3D) forest vegetation. Brief overviews of airborne laser scanning technology [often referred to as "light detection and ranging" (LIDAR)] and research findings on its use in forest measurement and monitoring are presented. Currently, many airborne laser scanning missions are flown with specifications designed for terrain mapping, often resulting in data sets that do not contain key information needed for vegetation measurement. Therefore, standards and specifications for airborne laser scanning missions are needed to insure their usefulness for vegetation measurement and monitoring, rather than simply terrain mapping (e.g., delivery of all return data with reflection intensity). Five simple, easily understood LIDAR-derived forest data products are identified that would help insure that forestry needs are considered when multiresource LIDAR missions are flown. Once standards are developed, there is an opportunity to maximize the value of permanent ground plot remeasurements by also collecting airborne laser data over a limited number of plots each year.

Keywords: LIDAR, airborne laser scanning, forest inventory, forest structure, forest monitoring

The goal of forest inventory is to provide accurate estimates of forest vegetation characteristics, including quantity, quality, extent, health, and composition within the area of interest. A forest inventory is an estimate of the makeup of plants (primarily trees) that comprise aboveground forest biomass. Ideally, a forest inventory system should be designed to provide spatial data that can be used over a range of scales to support a wide variety of resource management goals for a particular forest, including silviculture, harvest planning, habitat monitoring, watershed protection, and fuel management. However, traditional ground-based forest inventory methods are designed to provide point estimates of inventory parameters for relatively large areas to a desired level of precision and are not designed to provide spatially explicit, high-resolution mapped information regarding the spatial arrangement or structure of forest biological components over the landscape (Schreuder et al. 1993). However, such "biospatial" data are important in all aspects of natural resource management: the "where" often is as important as the "what." For most resource management activities, these biospatial data, characterizing how forest structure and composition vary over the landscape, are at least as important in economic, aesthetic, and habitat assessments as are geospatial data (e.g., slope, aspect, and elevation).

Over the last 10 years, a revolution in remote sensing technology has occurred, providing new tools for measuring and monitoring biospatial data across the landscape. The basis of this revolution is the ability to measure directly the three-dimensional (3D) structure (i.e., terrain, vegetation, and infrastructure) of imaged areas and to separate biospatial data (measurements of aboveground vegetation) from geospatial data (measurements of the terrain surface) using active remote sensing technologies. Active sensors emit energy (e.g., light or radio waves) and record the reflection of this energy down through the depth of the canopy. Two active remote sensing systems currently are commercially available with this capability: (1) airborne laser scanning, also referred to as light detection and ranging (LIDAR), and (2) interferometric synthetic aperture radar (IFSAR; also referred to as InSAR). Of these systems, LIDAR is more technically mature and widely available, although IFSAR holds much potential for landscape-level applications. In this article we focused on LIDAR as a tool for multiple resource inventory.

Brief Overview of Airborne LIDAR Technology

There are several varieties of airborne LIDAR systems; in this article we focused on the most common terrain mapping system, namely, discrete-return, small-footprint LIDAR (i.e., typical laser beam diameter at ground level in the range of 0.2–1.0 m). Discrete-return airborne LIDAR systems were

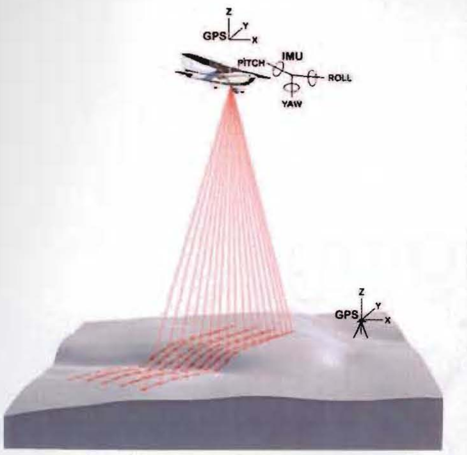

Figure 1. Schematic showing LIDAR data collection over bare ground.

developed over the last 15 years for the express purpose of mapping terrain (Wehr and Lohr 1999). Airborne laser scanning systems have four major hardware components: (1) a laser emitter-receiver scanning unit, (2) differential global positioning systems (GPS; aircraft and ground units), (3) a highly sensitive inertial measurement unit (IMU) attached to the scanning unit, and, of course, (4) a computer to control the system and store data from the first three components.

Laser scanners designed for terrain mapping emit near-infrared laser pulses at a high rate (typically 10,000–100,000/second). The precise position and attitude of the laser scanner unit at the time each pulse is emitted are determined from flight data collected by the GPS and IMU units. The range or distance between the scanner and an object that reflects the pulse is computed using the time it takes for the pulse to complete the return trip distance from scanner to object. This range information and the position and orientation of the scanner are used to calculate a precise coordinate for each reflection point.

A swath of terrain under the aircraft is surveyed through the lateral deflection of the laser pulses and the forward movement of the aircraft. The scanning pattern within the swath is established by an oscillating mirror or rotating prism, which causes the pulses to sweep across the landscape in a consistent pattern below the aircraft (Figure 1). Large areas are surveyed with a series of swaths that often overlap one another by 20% or more. This results in acquisition of a 3D "point cloud" from vegetation and terrain, often with several million measurements per square kilometer. The final pattern of pulse reflection points on the ground and the scanned swath width depend on the settings and design of the scanning mechanism (e.g., pulse rate, returns per pulse, and scanning angle), as well as other factors such as flying height, aircraft speed, and the shape of the topography.

Most LIDAR systems can detect several reflections or "returns" from a single laser pulse. Multiple returns occur when the pulse strikes a target that does not completely block the path of the pulse and the remaining portion of the pulse continues on to a lower object. This situation frequently occurs in forest canopies that have small gaps between branches and foliage. To take advantage of this, most terrain mapping missions over hardwood or mixed conifer-hardwood forest are flown in leaf-off conditions to maximize the percentage of pulses that reach the ground surface. In contrast, when the primary objective is characterization of canopy conditions, LIDAR missions are sometimes flown in leaf-on conditions to maximize the number of returns from tree crowns and other vegetation layers.

System manufacturers have expended great efforts to develop methods for distinguishing between laser reflections from the ground surface (terrain measurements) and those from vegetation. LIDAR system manufacturers typically quote root mean squared errors of 10–15 cm vertical and 50–100 cm horizontal for terrain mapping products under optimal conditions. In several studies the vertical accuracy of LIDAR terrain measurements was found to be in the range of 15–50 cm over a variety of ground and cover conditions from open flat areas (Pereira and Janssen 1999) to variable forest cover (ranging from clearcuts to mature stands; Kraus and Pfeifer 1998, Reutebuch et al. 2003).

Airborne LIDAR scanning system capabilities have dramatically increased over the last 10 years. Data acquisition costs have correspondingly decreased as advances in inertial navigation systems, computing capability, and GPS technology have allowed LIDAR to move into the mainstream commercial terrain mapping sector. Today, several vendors market LIDAR systems, and several third-party vendors offer specialized LIDAR data processing software for efficient terrain mapping. Numerous LIDAR survey firms offer a complete range of mapping services including the generation of digital terrain models, contour maps, extraction of infrastructure locations and characteristics, and delivery of processed scanner data in a variety of formats.

LIDAR-Derived Forest Measurements

Although the mapping community has embraced LIDAR as the standard technology for collecting high-resolution geospatial data over vegetated areas, the natural resource management community has been slower to appreciate the capability of LIDAR to simultaneously collect high-resolution biospatial data. System manufacturers have largely ignored the potential uses of the LIDAR vegetation returns (that are understandably considered "noise" in the context of terrain mapping), and only in the last few years have natural resource scientists begun to realize the accuracy and value of LIDAR biospatial forest structure data, with Canada and Europe at the forefront (Wulder et al. 2003, Olsson and Næsset 2004). There are a multitude of uses for such 3D forest structure data, not the least of which is forest inventory and monitoring. Several European countries have initiated programs to use LIDAR for large-scale forest inventory; however, forest analysis procedures are not as well refined as are those for terrain mapping products. Scandinavian researchers (Næsett et al. 2004) have reported generally very good results with LIDAR measurements of height, volume, stocking, and basal area in coniferous areas with LIDAR point densities ranging from 0.1 to 10 points m^{-2}. Although there is growing interest in the operational use of LIDAR for large-scale resource inventory applications in the United States, to date, most of the activity has been limited to research applications.

LIDAR-Based Measurement of Individual Tree Attributes

Individual tree crowns composing the canopy surface can be detected and measured automatically with relatively high accuracy through the application of computer vision algorithms (Figure 2) when LIDAR data are acquired at a high density (4–5 points m^2). Several studies have shown that when the canopy is composed of a single canopy stratum, morphological computer vision techniques can be used effectively to identify automatically tree crown structures and measure individual tree attributes, including total height, crown height, and crown diameter (Ziegler et al. 2000, Persson et al. 2002, Schardt et al. 2002, Andersen 2003, Straub 2003). Popescu et al. (2003) have shown that although individual tree heights can be estimated using lower-density LIDAR data (1 point m^{-2}), it is difficult to

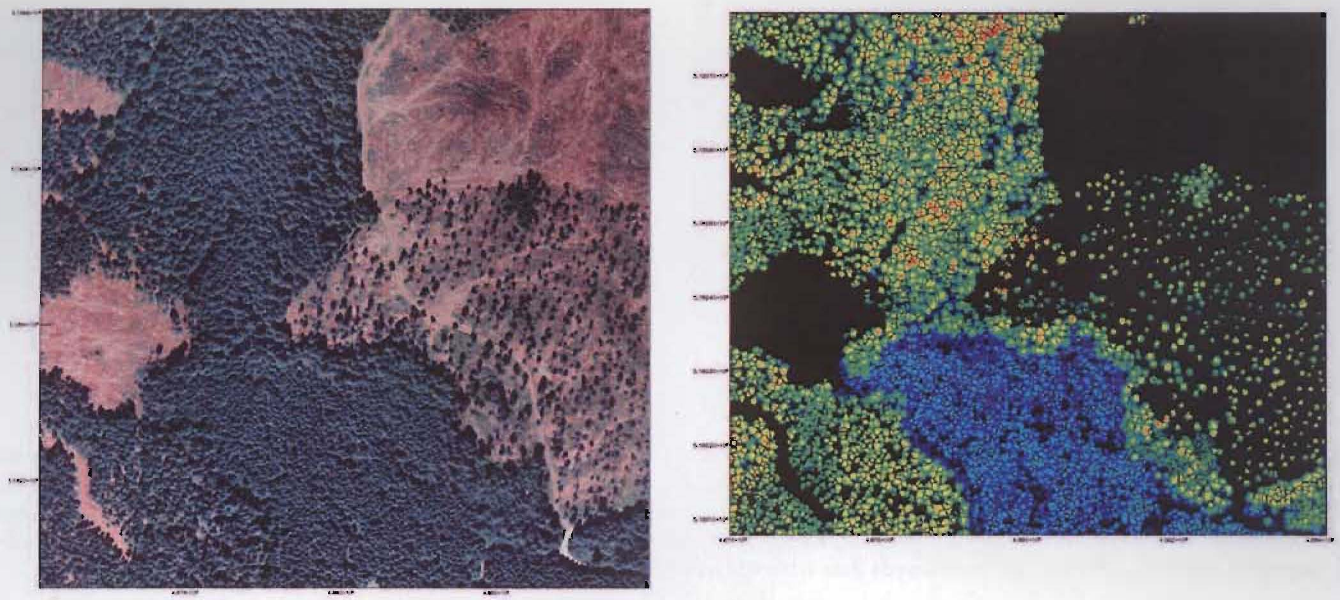

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Figure 2. (A) Orthophotograph of selected area (courtesy of Washington Department of Natural Resources), and (B) individual tree-level segmentation of the LIDAR canopy height model via morphological watershed algorithm (color-coded by height; black lines indicate boundaries around crowns).

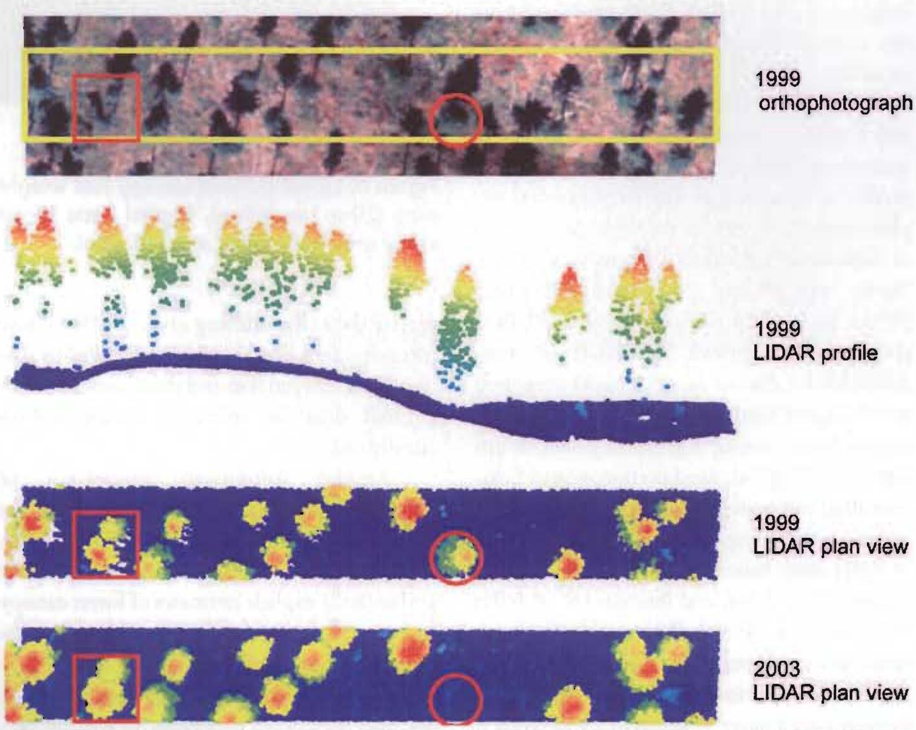

Figure 3. Comparison of 1999 and 2003 LIDAR crown measurements in a heavily thinned strip of mature forest in the Capitol State Forest study area. (From top to bottom) 1999 orthophotograph; profile view of all 1999 LIDAR points (color-coded by height aboveground) measured within the yellow box shown in the orthophotograph; plan view of all 1999 points; and, plan view of all 2003 points. Note the crown expansion between 1999 and 2003 that is apparent in the red square and the tree that was removed (because of windthrow) apparent in the red circle.

measure accurately other crown attributes, such as crown width, especially in mixed deciduous forest types. Several studies have shown that the combined use of LIDAR and multispectral digital imagery can lead to more accurate individual tree- and plot-level estimates of critical inventory variables such as height, stem volume, basal area, biomass, and stem density (McCombs et al. 2003, Popescu et al. 2004).

When high-density LIDAR data sets are available from different years, the difference in the individual tree canopy measurements generated from the multitemporal LIDAR data sets represents an estimate of the tree growth over the intervening period (Yu et al. 2004). In Figure 3, one can clearly see the expansion of individual tree crowns and the removal (due to windthrow in this case) of an individual crown by comparing LIDAR data clouds from 1999 and 2003 for the same strip of forest. The use of multitemporal LIDAR therefore has the potential for monitoring growth and mortality for all overstory trees within a certain area. As an example, in a study performed at the Capitol State Forest study area in western Washington State, Andersen et al. (2005a) used high-density LIDAR data acquired in early 1999 and late 2003 to extract individual tree height growth measurements for 1.2 km^2 of mountainous second-growth, naturally regenerated Douglas-fir forest (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*). Preliminary results of this analysis showed that subtle differences in growth between thinning treatment units can be detected even over this relatively short period of time (five growing seasons). Height growth was less pronounced in the mature (age 75 years)

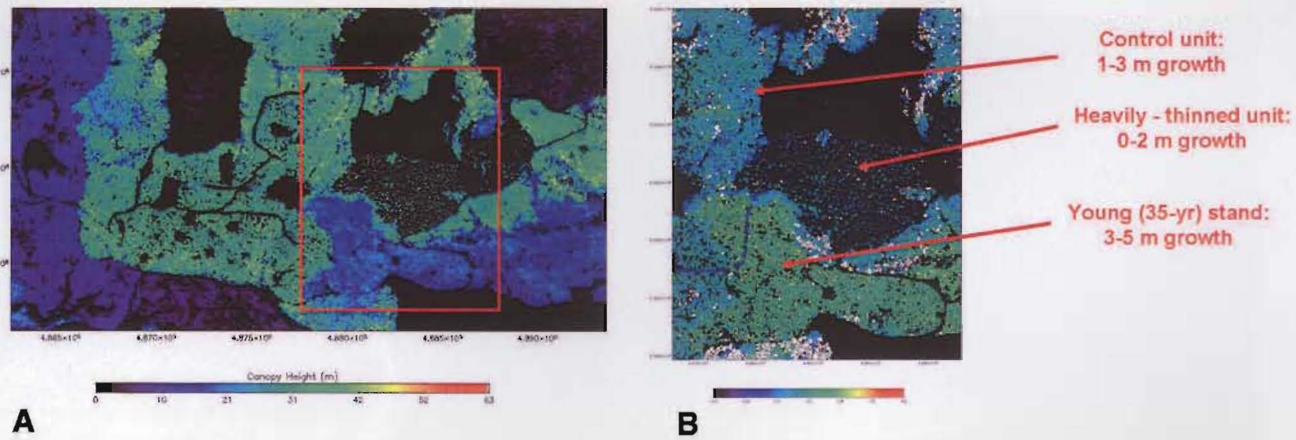

Figure 4. LIDAR-based measurement of individual conifer tree growth (1999–2003). (A) Selected area within Capitol State Forest study area shown in LIDAR canopy height model color-coded by canopy height, and (B) LIDAR-derived individual tree height growth measurement color-coded by height growth. A significant difference in height growth between stands is evident [control (75-year-old, unthinned stand) approximately 1–3 m in growth; young (35-year-old stand) approximately 3–5 m; heavily thinned (75-year-old stand) approximately 0–2 m]. Segments colored white indicate hardwoods that were excluded from this conifer growth analysis.

heavily thinned unit (approximately 0–2 m), where the primary response to the treatment was increased crown expansion, than in the mature unthinned control unit, where the height growth was in the range of 1–3 m (Figure 4). Not surprisingly, the height growth within a younger (age 35 years) stand was much higher (approximately 3–5 m) than in the mature stands. The capability of LIDAR to measure accurately the growth rates of individual dominant and codominant trees across an entire forest clearly provides an opportunity for much more accurate and spatially explicit assessment of site quality and growth analysis.

Plot-Level LIDAR-Based Forest Structure Measurement

The basic principles of allometry, or laws of proportional growth, can be used to quantitatively model the relationship between the dimensions of various components of a forest system, including canopy height, biomass, basal area, and foliar surfaces (West et al. 1997). These principles can be used to develop regression models relating the spatial distribution of LIDAR returns within a plot area to plot-level stand inventory variables (e.g., height, volume, stocking, and basal area) because LIDAR measurements essentially represent a detailed measurement of all reflecting surfaces within a canopy volume (foliage, branches, and stems). This approach is appropriate when LIDAR data are collected at a lower density (i.e., 1- to 2-m spacing between points) or the vertical structure of the forest is complex (i.e., composed of multiple canopy strata, perhaps with a significant understory component). The metrics used to describe the spatial distribution of LIDAR returns in a plot area include height percentiles, mean height, maximum height, coefficient of variation of height, and a LIDAR-derived measure of canopy cover (e.g., percentage of LIDAR first returns above 2 m). This plot-level approach has been used by researchers in North America and Europe to estimate stand inventory parameters in several different forest types, where predictive regression models were shown to explain from 80 to 99% of the variation (i.e., R^2) in field-measured values (Means et al. 2000, Næsset and Økland 2002, Lim and Treitz 2004). In a study performed using 99 field plots in second-growth Douglas-fir (*P. menziesii (Mirb.) Franco var. menziesii*) measured at the Capitol State Forest study area in Washington State, strong regression relationships between LIDAR-derived predictors and field-measured values were found for several critical inventory parameters, including basal area ($R^2 = 0.91$), stem volume ($R^2 = 0.92$), dominant height ($R^2 = 0.96$), and biomass ($R^2 = 0.91$; Andersen et al. 2005a). Because this approach relies on a single mathematical model to relate the LIDAR metrics to a given inventory parameter over a range of different stand types, it is important to obtain representative plot-level field data that capture the full range of variability present in the area of LIDAR coverage. Recent research in the West Virginia mixed hardwood forests also has indicated that the intensity data (sometimes referred to as "reflectance") of the NIR reflection from LIDAR data acquired in leaf-off conditions are useful for some hardwood species classifications when used in conjunction with LIDAR geometric data (Brandtberg et al. 2003). These intensity data likewise can be helpful to distinguish between live and dead crowns when LIDAR data are collected during leaf-on conditions.

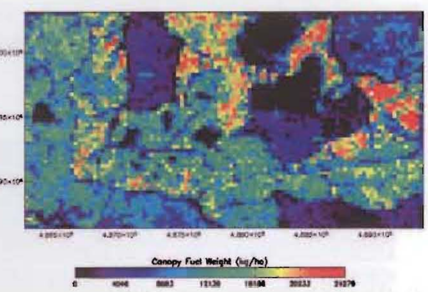

Figure 5. LIDAR-derived canopy fuel weight map (30-m resolution), Capitol State Forest study area (Andersen et al. 2005b).

Another promising application of LIDAR technology to forest inventory is in the area of canopy fuel mapping (Riano et al. 2004). Resource managers rely on accurate and spatially explicit estimates of forest canopy fuel parameters, including canopy cover, canopy height, crown bulk density, and canopy base height to support fire behavior modeling and fuel mitigation programs. In a study performed at the Capitol State Forest, regression analysis was used to develop strong predictive models relating a variety of LIDAR-based forest structure metrics to plot-level canopy fuel estimates derived from field inventory data [sqrt(crown fuel weight), $R^2 = 0.86$; ln(crown bulk density), $R^2 = 0.84$; canopy base height, $R^2 = 0.77$; canopy height, $R^2 = 0.98$ (Andersen et al. 2005b)]. These regression models then can be used to generate digital maps of canopy fuel parameters over the extent of the LIDAR coverage. Canopy fuel weight, e.g., can be mapped over the landscape (Figure 5).

Need for LIDAR Mission Standards and Specifications

Today, we are in a position with LIDAR technology similar to where our predecessors were with aerial photography in the early part of the last century. By 1930, it was obvious that aerial photography was providing new data on the extent, composition, and volume of forests, as well as information for many other natural resource management activities; yet it took many more years for agencies to develop flight specifications and cooperative, cost-sharing agreements to allow periodic wide-area photography missions. It is increasingly evident that LIDAR provides 3D geo- and biospatial data at an unprecedented level of detail and accuracy, but standards and specifications have not been established for collecting LIDAR data suitable for use in a wide range of natural resource management activities. At the same time, many large LIDAR projects (county- and statewide acquisitions) are being flown by a multitude of local, state, and federal agencies for single-use management needs (e.g., flood risk mapping, updated digital elevation models (DEM), or geologic fault detection), often without consideration as to how the data might be used for forest vegetation measurements and monitoring. Many LIDAR data sets, for instance, are being flown without collecting (or without requiring delivery to the client) return intensity information that is very useful for discerning forest types or identifying mortality, and in some cases, species differences. Furthermore, many contracts also have not required delivery of all returns—they simply specify bare-ground DEMs or a filtered subset of the data that only includes ground points. Vegetation data often are lost or must be repurchased from the vendor.

There is an immediate need to start developing standards and specifications for LIDAR data collections so that data are more widely available for use by local, state, and federal natural resource management agencies. Again, the multiagency working groups and agreements established to organize the collection and distribution of periodic aerial photography provide models for how coordinated LIDAR projects could be planned and financed to insure that future data acquisitions meet multiresource needs. The Federal Emergency Management Agency (FEMA) has taken the lead in establishing guidelines and specifications for LIDAR terrain mapping for flood hazard mapping (FEMA 2003); however, there has not been a similar coordinated effort between natural resource management agencies. The FEMA standards provide a good starting point on which to build more comprehensive standards that meet multiresource needs.

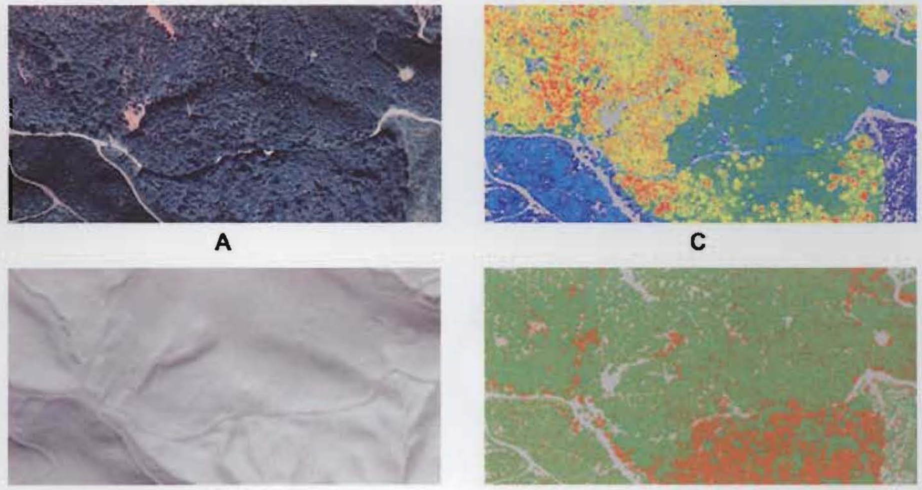

Figure 6. Comparison of a traditional color orthophotograph to LIDAR-derived images for the same area: (A) orthophotograph; (B) bare-ground DEM; (C) CHM (canopy height is less than 2 m in gray areas); and (D) canopy cover image colored by leaf-off LIDAR intensity, where brown low-intensity areas indicate hardwood cover and green high-intensity areas indicate conifer cover.

Standards and specifications are needed for LIDAR missions (sensor settings and flight specifications) and for delivered products. There has been limited research on needed flight and sensor specifications. Evans et al. (2001) proposed research to examine the effects of LIDAR flight and sensor specifications over forests of differing density and spatial arrangements. A more coordinated, comprehensive research effort is needed to develop data collection standards and specifications over a more complete range of forest conditions. In addition, standards are needed for products of LIDAR missions to insure their usefulness for forest measurements.

To stimulate development of both types of standards and specifications, there are several simple, easily understood and widely recognized LIDAR-derived forest mapping products that many agencies and specialists within organizations would find useful. The following five could be generated easily, assuming consistent data collection standards are implemented:

1. High-resolution (1–5 m) bare-ground DEM. These DEMs provide improved data for many applications including hydrologic and erosion process modeling, landscape modeling, road and harvest planning and design, and geographic information system analysis (Figure 6B).
2. Canopy height models (CHM). CHMs provide spatially explicit stand structure data over the landscape for estimation of growing stock, input for habitat and fire models, and any other resource planning activities where spatial arrangement and tree height are important considerations (Figure 6C).
3. Canopy cover maps. These images provide a direct measurement of cover by height aboveground. Figure 6D illustrates canopy cover where canopy height is greater than 2 m.
4. LIDAR intensity images. These high-resolution images can be matched with existing orthophotographs and other digital imagery for change detection and monitoring over time. They also are useful in verifying the registration of LIDAR data with other geospatial data layers. As shown in Figure 6D, intensity data can be used in conjunction with CHMs to identify hardwood (brown) and conifer canopy areas (green).
5. All returns data set. This archive of all the

LIDAR returns and their associated reflectance intensity could be used for a wide range of specialized analysis and provides baseline data on current terrain and vegetation structure that could be used in the future for change detection and monitoring (e.g., crown expansion or dieback). At a minimum, this data set should include pulse number, return number, east coordinate, north coordinate, elevation, and return intensity for each LIDAR return and metadata documenting the LIDAR mission flight parameters, sensor type and settings, GPS control, horizontal and vertical datum, coordinate units and projection, and date and time of mission. Ideally, all return data files should be in the American Society for Photogrammetry and Remote Sensing LIDAR data exchange format.

Leveraging Ongoing Ground Plot Measurements

Several projects have reported excellent results using LIDAR in double-sampling forest inventory approaches (Næsset 2002, Parker and Evans 2004). The Forest Inventory and Analysis program (FIA), USDA Forest Service, is continually measuring permanent sample plots in the United States that could be used over time to develop robust LIDAR regression estimators for major canopy variables. However, for FIA plots to be useful in double-sampling regression analysis, plot locations will need to be measured more accurately than is the current practice (nominally 10 m, but likely 10–50 m). Ideally, locations should be accurate to within a meter (well within the capabilities of differentially corrected GPS surveys) to allow LIDAR point clouds to be aligned correctly with ground plots. Ironically, with the development of highly precise direct georeferencing systems for airborne sensors, now, it is often more difficult to obtain accurate GPS ground positions, because of canopy interference with GPS reception, than it is to georeference airborne remote sensing data. Given the large ongoing investment that is being made in remeasurement of ground plots, it would seem that a small proportion of these ground plots (carefully selected to cover a wide range of forest stand conditions) should be located more carefully. LIDAR data could then be collected during the same season over these plots. Within a few years, an extensive archive of spatially aligned ground and LIDAR plot data would be available for development of regression models. These regressions would then be available for use with any large-area LIDAR data set (past or future) to estimate forest inventory parameters or other vegetation variables for use in a multitude of land-management exercises. This would provide a valuable method for spatially explicit monitoring of forest change with unprecedented accuracy and resolution.

Conclusions

Over the last 5 years, numerous studies have shown that LIDAR data can provide high-resolution biospatial data for multiresource management and analyses including traditional forest inventory and more specialized single-use analysis (e.g., canopy fuel estimates for fire behavior modeling). Simultaneously, LIDAR has emerged as the leading technology for high-resolution terrain mapping, spurring the development of national guidelines and standards in this domain. It appears there is a similar need to develop national standards and guidelines for LIDAR data collection for forest vegetation measurement and monitoring to insure that the maximum value can be returned from future LIDAR projects over forested regions. Focusing attention on such standards may also encourage LIDAR manufacturers to modify scanners for more optimal sensing of vegetation, rather than simply terrain, particularly given the need for monitoring forest change. Finally, the usefulness and value of ongoing permanent ground sample plot measurements could be leveraged by collecting more accurate plot locations and collecting limited sets of LIDAR data over these plots.

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