FOREST MEASUREMENT AND MONITORING USING HIGH-RESOLUTION AIRBORNE LIDAR

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ABSTRACT

Airborne laser scanning has emerged as a highly-accurate, high-resolution forest survey tool, providing the opportunity to develop and implement forest inventory and monitoring programs using a level of detail not previously possible. In this paper, we will present results from several research studies carried out at a study area within Capitol State Forest in the state of Washington, where we investigated the utility of LIDAR for measurement of terrain and forest structure characteristics. Previous studies at this site have shown that LIDAR can be used to accurately measure terrain elevation even under dense forest canopy. The results of another study have indicated that LIDAR can also be used to accurately estimate a number of forest inventory variables, including basal area, stem volume, dominant height, and biomass. The laser-reflection intensity information provided by LIDAR can also be used for species classification. Individual tree crowns can be recognized by using computer vision algorithms applied to a detailed LIDAR-based canopy surface model. This approach can be used to extract measurements of individual trees, including top height and crown base height. Preliminary results have shown that if high-density LIDAR data are collected in different years, measurements of individual-tree height growth can be obtained for an entire forest area, allowing for detailed, spatially explicit analyses of site quality and productivity.

KEYWORDS: Forest measurement, remote sensing, LIDAR, terrain mapping, canopy mapping.

INTRODUCTION

The development of high-resolution, active remote sensing measurement systems has the potential to support the development and application of highly site-specific to forest management. One of the more promising forest remote sensing tools to emerge in recent years is small-footprint airborne laser scanning, or light detection and ranging (LIDAR). LIDAR is an optical remote sensing technology capable of providing direct three-dimensional (3-D) measurements of forest canopy structure. The components of an airborne LIDAR system include a laser scanner, which emits from 7,000 to 100,000 laser pulses each second, coupled with a precise airborne positioning system, which uses differentially corrected GPS (global positioning system) and an inertial measurement unit to accurately determine the position and orientation of the scanner at the moment each pulse is emitted[3]. Because the speed of light is a known constant, the distance corresponding to each laser reflection from the ground can be calculated from the time delay between the emission and reception of the laser pulse. This distance is used along with the position and orientation information to calculate the 3-D coordinates of each reflection. Most airborne LIDAR systems designed for topographic mapping applications use lasers with wavelengths in the near-infrared region of the electromagnetic spectrum. These sensors typically use a system of oscillating or rotating mirrors to generate a scan pattern of measurements in a swath beneath the aircraft (fig. 1). LIDAR

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[3] LIDAR systems are typically classified into two types, depending upon the size of the "footprint" for the laser pulse. "Small footprint" systems have ground spot sizes from 0.1 to 1 m, whereas "large-footprint" systems have spot sizes from 5 to 100 m. Given that large footprint, continuous waveform LIDAR systems are neither commercially available nor capable of providing high-resolution data, in this paper we restrict our discussion to the use of small-footprint, discrete-return LIDAR data. The application of large-footprint LIDAR to forestry applications has been discussed in Harding et al. (2001) and Lefsky et al. (2002).

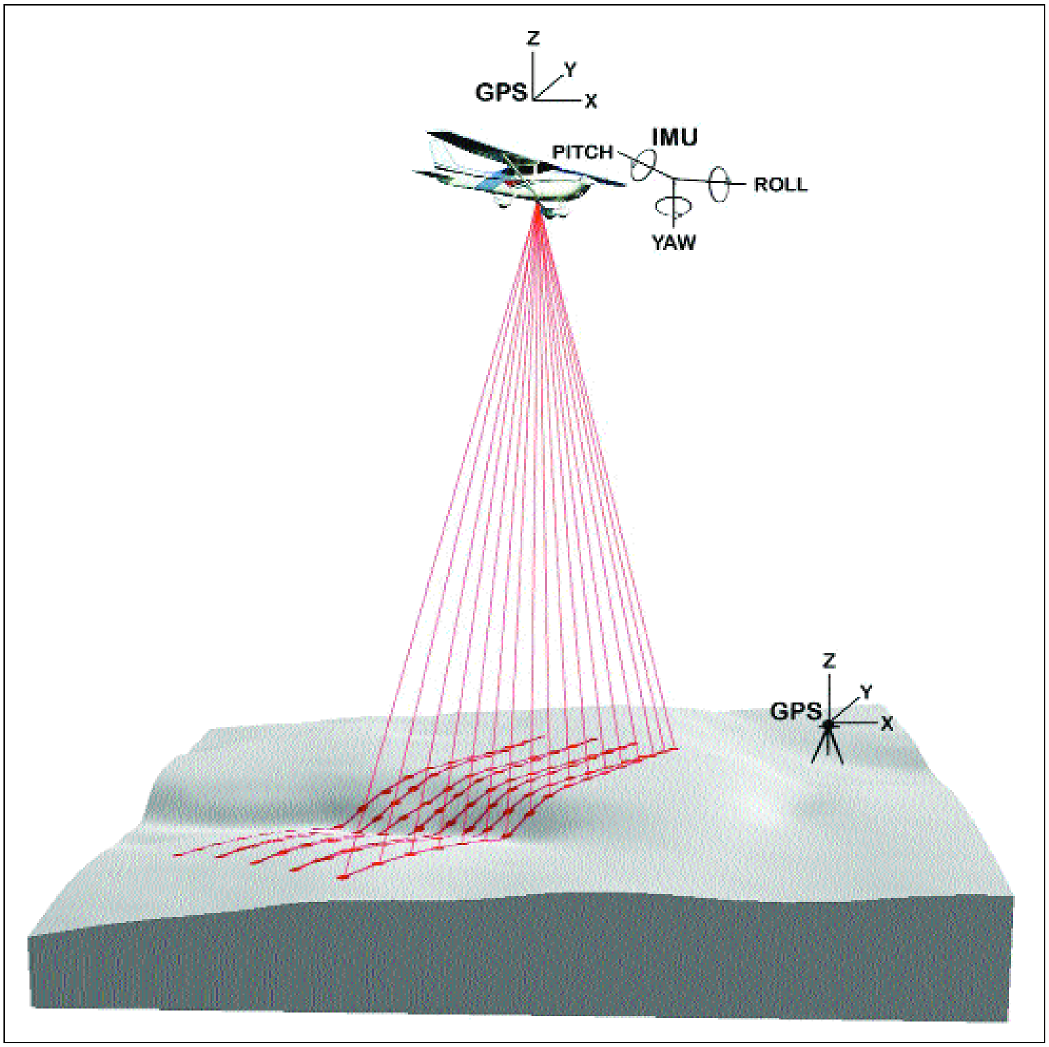


Figure 1—Components of an airborne laser scanning (LIDAR) system.

systems typically collect data at a density between 0.5 and 4 pulses per square meter and with a pulse diameter between 0.4 and 0.7 m, depending upon the specific system and flight parameters for the project. Many LIDAR systems also have the capability to detece several reflections from a single pulse. In a forested area, LIDAR pulses reflect from the canopy foliage, branches, understory vegetation, and the terrain surface. The LIDAR point cloud therefore represents a detailed 3-D measurement of the spatial organization of canopy materials (foliage, branches, stems, shrubs, etc.) down to the ground surface for the scanned area. Quantitative metrics describing the spatial distribution of these LIDAR returns will therefore be related to a wide variety of critical forest structure metrics, including dominant height, basal area, stem volume, and biomass. A highly detailed model of the canopy surface can be generated by using the LIDAR returns from the surface of the canopy. The application of computer vision (object recognition) algorithms then allows individual tree crowns composing the canopy to be isolated and measured. Furthermore, if LIDAR data are acquired over the same area of forest in different years, detailed measurements of forest change (mortality and forest growth) can be obtained. In this paper, we present the results of a study investigating the use of LIDAR for forest measurement and monitoring in a conifer forest within western Washington state.

STUDY AREA

The study area for this project was a 5.2 km^2 area within Capitol State Forest in western Washington (fig. 2). This forest is composed primarily of coniferous timber species, including Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja*

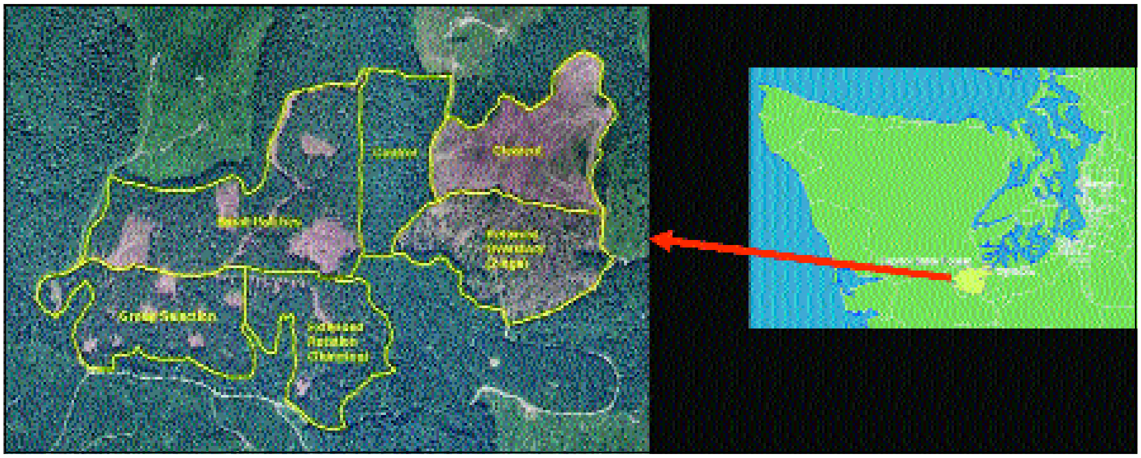


Figure 2—Capitol Forest study site. Image courtesy of Washington State Department of Natural Resources.

plicata), along with various hardwood species, including red alder (*Alnus rubra*) and big-leaf maple (*Acer macrophyllum*). This area is the site of an on-going silvicultural trial investigating the effects of several different harvest treatments designed to create a variety of residual stand densities (clearcut unit: 0 trees per hectare (TPH); heavily-thinned unit[4]: 40 TPH; lightly-thinned unit: 175 TPH; and control unit: 280 TPH).

A total of 99 inventory plots were established within this study area, extending over a range of stand types including young stands (about 35 years) and mature stands (about 70 years) with variable stand densities. Plot sizes ranged from 0.02 to 0.2 ha. A variety of measurements were obtained at each plot, including species and diameter at breast height for all trees greater than 14.2 cm in diameter. Additional measurements of total height and height-to-live-crown were acquired for a representative selection of trees over the range of diameters by using a handheld laser rangefinder. A detailed description of the plot measurement protocol can be found in a previous report (chapter 3, Curtis et al. 2004).

LIDAR DATA

High-density LIDAR data were acquired over the study area in the spring of 1999 and the summer of 2003, a period that represented five growing seasons. The 1999 LIDAR data were acquired with a SAAB[5] TopEye system operated from a helicopter platform in the spring of 1999 (leaf-off conditions). The 2003 LIDAR data were acquired with a Terrapoint ALTMS system operating from a fixed-wing platform in September 2003 (leaf-on conditions). Both data sets were acquired with a nominal density of 4 returns (or reflections) per square meter. The vendor provided raw LIDAR data consisting of XYZ coordinates and return-intensity information for all LIDAR returns in an ASCII text format. In addition, the vendor provided "filtered ground" data representing ground returns isolated via a proprietary filtering algorithm. The filtered ground returns from the 1999 data set were used to generate a 1.52-meter (5 ft) digital terrain model (DTM) over the entire study area, using the Surfer software system (Golden Software, Inc. 1999) with the inverse distance interpolation algorithm and a 4-sector search with a radius of 60 m (fig. 3). The same gridding algorithm was used to generate a 1-m DTM from the filtered ground 2003 LIDAR data (fig. 4).

LIDAR-BASED TERRAIN MEASUREMENT

In a previous study, the accuracy of the 1999 LIDAR-based DTM was assessed via comparison to 347 high-accuracy topographic checkpoints collected using survey-grade equipment (Reutebuch et al. 2003). This study showed that the LIDAR-derived DTM had a mean error of +0.22 m with a standard deviation of 0.24 m. This study showed that the accuracy of the DTM is slightly reduced by the presence of heavy canopy or near-ground vegetation. A similar accuracy assessment of the 2003 LIDAR-based terrain model showed that the DTM had a mean error of +0.31 m with a standard deviation of 0.34 m. The difference between the 1999 and 2003 DTM errors is statistically significant (at $\alpha = 0.05$), and may be attributed to the fact

[4] The heavily-thinned unit is called the 2-aged stand in Curtis et al. 2004.

[5] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product of service.

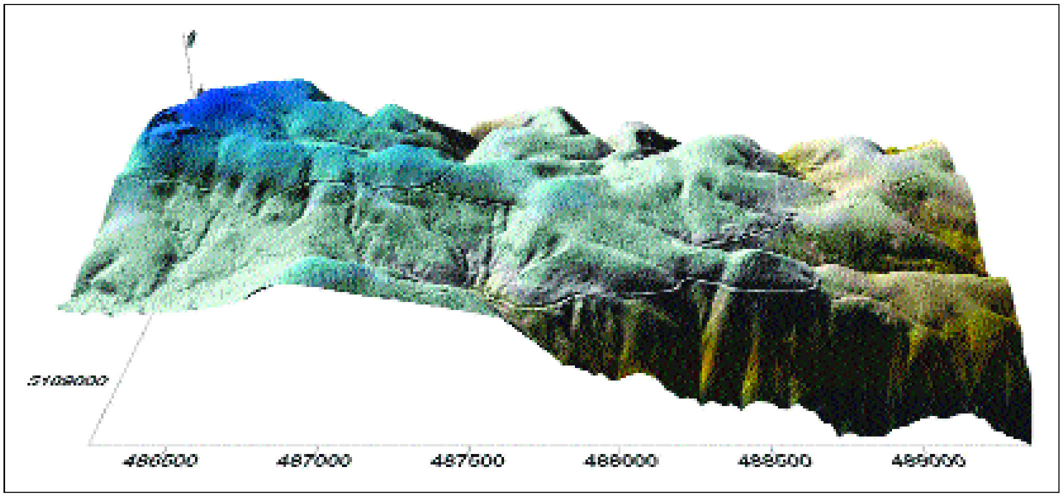


Figure 3—1999 LIDAR digital terrain mode (UTM coordinate system).

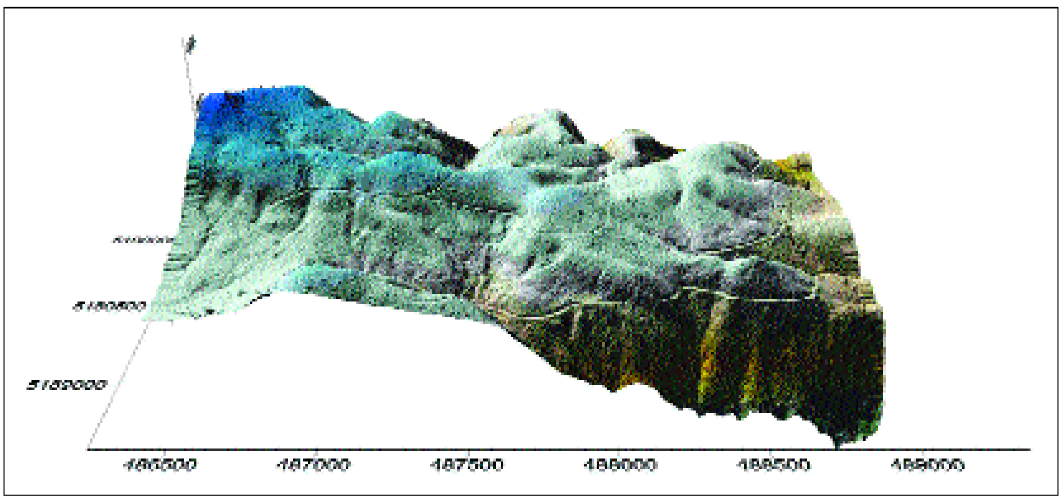


Figure 4—2003 LIDAR digital terrain model.

that the 2003 LIDAR was acquired in leaf-on conditions whereas the 1999 LIDAR was acquired in leaf-off conditions. In leaf-on conditions, it can be expected that fewer LIDAR pulses will penetrate through deciduous t r e e crowns. In addition, there was significant growth of the near-ground vegetation in the treated areas between 1999 and 2003 that could also have an effect on DTM accuracy. However, the difference between the mean error of the leaf-off1999 DTM and the leaf-on 2003 DTM is remarkably small, indicating that LIDAR is capable of measuring terrain under this predominantly coniferous forest canopy at a very high accuracy in both leaf-on and leaf-off conditions.

LIDAR-BASED FOREST MEASUREMENT

Canopy Surface Measurement

LIDAR canopy surface measurements were extracted by filtering out the highest return within each 1-m grid cell area. These filtered "canopy-level" returns were then gridded into a canopy surface model again using an inverse distance interpolation algorithm and a 3-sector search with a radius of 3 m. The 1999 LIDAR canopy surface model is shown in figure 5, and the 2003 LIDAR canopy model is shown in figure 6. In a comparison to profiles and spot height measurements acquired from large-scale aerial photographs, the difference between photogrammetric canopy height and 1999 LIDAR canopy height measurements

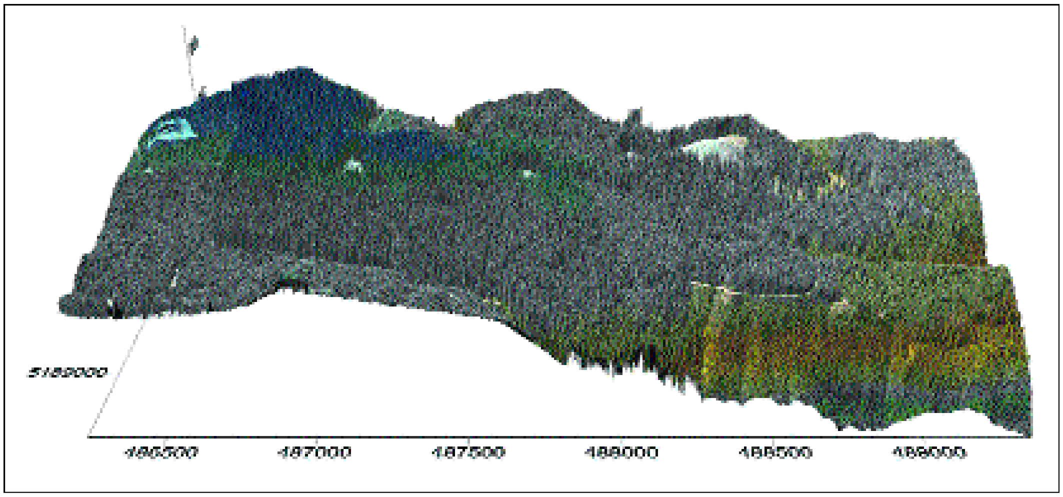


Figure 5 –1999 LIDAR canopy surface model.

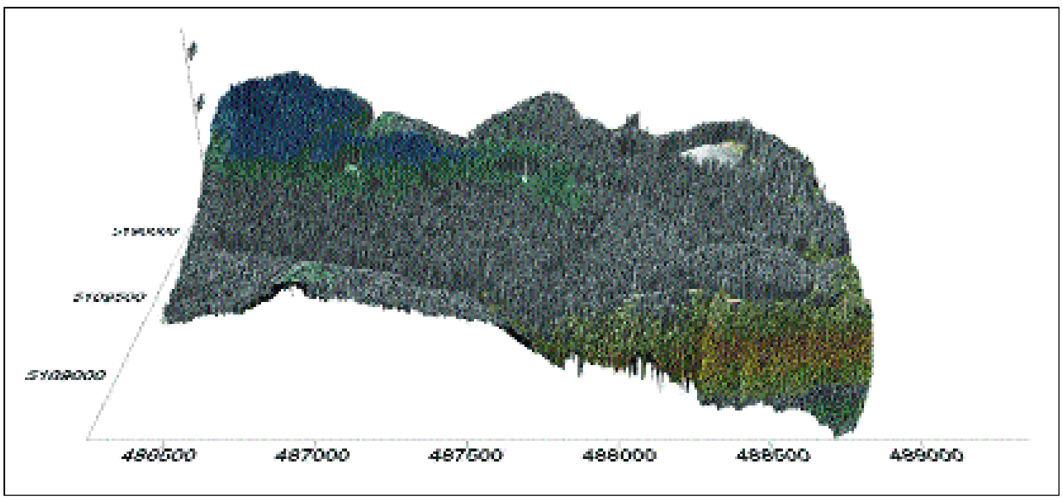


Figure 6—2003 LIDAR canopy surface model.

(after accounting for tree growth) was found to be within approximately 1 m (Andersen et al. 2003). The detailed LIDAR-derived canopy surface model provides a rich description of overstory canopy structure, including information on canopy cover, gap distribution, and individual tree dimensions (Andersen, 2003).

Species Recognition

Several previous studies have shown that the intensity information provided for each LIDAR reflection can be used to classify by species type (Andersen et al., in prep., Brandtberg et al. 2003, Holmgren and Persson, 2004). Brandtberg and others used summary statistics of the height distribution and intensity values within individual tree crown segments to classify tree species within an eastern deciduous forest in West Virginia (Brandtberg et al. 2003). In another study carried out in Sweden, LIDAR-derived metrics describing structural and reflectance characteristics of individual tree crowns were used to discriminate between spruce and pine trees (Holmgren and Persson 2004). In leaf-off conditions, the near-infrared reflectance from hardwood tree crowns (and dead trees) is significantly lower than that from coniferous crowns (fig. 7). Preliminary results indicate that leaf-off LIDAR can be used to accurately classify tree crowns into hardwood-softwood classes (Andersen et al., in prep.). This capability may be particularly important in determining species composition for riparian zone management.

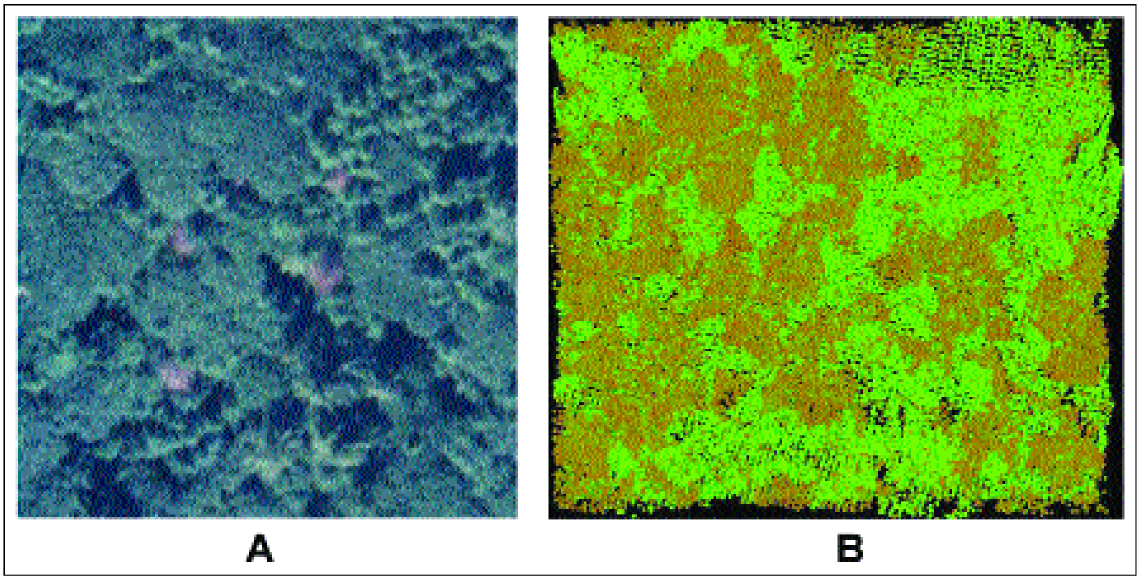


Figure 7—Species classification using LIDAR intensity data a) leaf-on orthophoto, b) leaf-off hardwoods and dead trees (brown), conifers (green).

Plot-Level Measurement

The vertical distribution of LIDAR data within a given area provides a detailed description of forest structure (fig. 8). Regression techniques can be used to model the relationship between a set of metrics describing the vertical distribution of LIDAR canopy returns within a plot area (e.g., 0.1 ha) and stand structure variables derived from a plot tree list. Given the allometric relationships between canopy dimensions and biomass, governed by the laws of proportional growth, there is a strong physical basis for the quantitative relationship between the distribution of LIDAR measurements, which are essentially characterizing the density of canopy foliage, and stand variables such as biomass, stem volume, and basal area (West et al. 1997). The metrics used to characterize the vertical distribution of LIDAR measurements within a plot include various height quantiles (e.g., 10th, 20th, …, 90th percentile heights), as well as other metrics such as mean height, maximum height, coefficient of variation of height, and a LIDAR-derived measure of canopy cover (calculated as the percentage of LIDAR first returns that reflect from the canopy level [i.e., more than 2 m above the ground]). Once these regression models are developed to establish the quantitative relationship between the LIDAR metrics and the inventory parameters, these predictive models can be used to generate maps of various stand parameters over the entire extent of the LIDAR coverage. With this approach, however, it is important to collect plot-level inventory data over the full range of stand conditions present in the mapped area. If stand conditions exist that fall outside of the plot types used to generate the predictive models, the estimates are in effect extrapolations outside the range of data and will be unreliable. Because this approach relies only on the vertical distribution of LIDAR returns and is not dependent on accurate measurement of individual tree crowns, it is particularly useful when the LIDAR data density is relatively low (<1 return/m^2). This approach uses LIDAR data acquired throughout the full depth of the forest canopy, including the understory layer, and therefore provides a more comprehensive estimate of stand parameters than the individual-tree approach described in the next section, which is

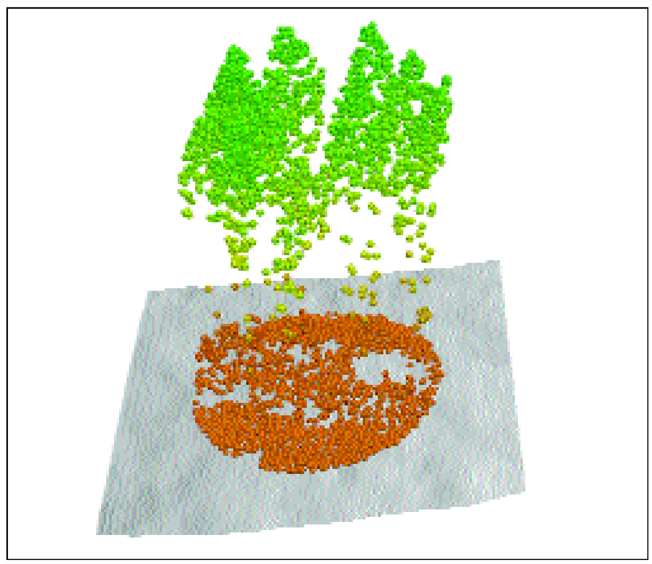


Figure 8—Distribution of LIDAR returns within a 0.8 ha (0.2 ac) plot area, Capitol Forest study area)

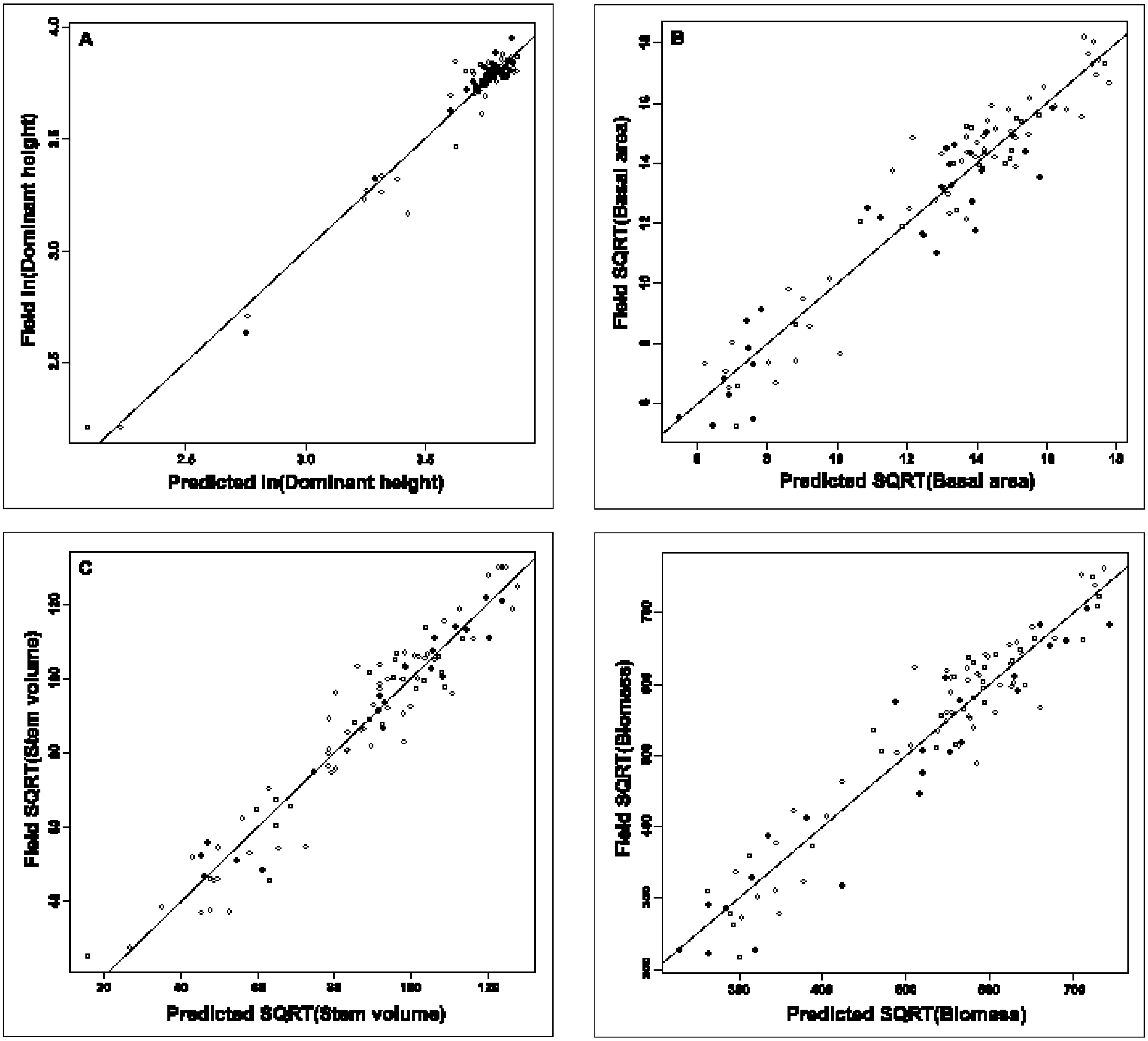


Figure 9—Results of plot-level LIDAR-based estimation of forest inventory parameters at Capitol Forest study site. Scatterplots represent relationship between predicted (*x*) and field-based (*y*) estimates at the individual plots for a) dominant height, b) basal area, c) stem volume, and d) biomass. Lines represent 1:1 relationship.

limited to the overstory layer. This plot-level approach to LIDAR-based forest inventory has been applied across a variety of forest types by researchers in North America and Europe (Means et al. 2000, Naesset 2002, Naesset and Okland 2002). In a study done at the Capitol Forest study area, strong regression relationships were found between LIDAR-derived predictor variables and field-measure inventory variables, 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) (fig. 9). This plot-level approach has also been used to estimate canopy fuel variables, including canopy height, canopy bulk density, and canopy base height at the Capitol Forest study site (Andersen et al. 2005).

Individual Tree-Level Measurement

If LIDAR data are acquired at a high enough density, details at the scale of individual tree crowns can be resolved in the LIDAR-derived canopy surface model (fig. 5). A previous study showed that individual tree attributes, including tree height and crown base height, could be accurately

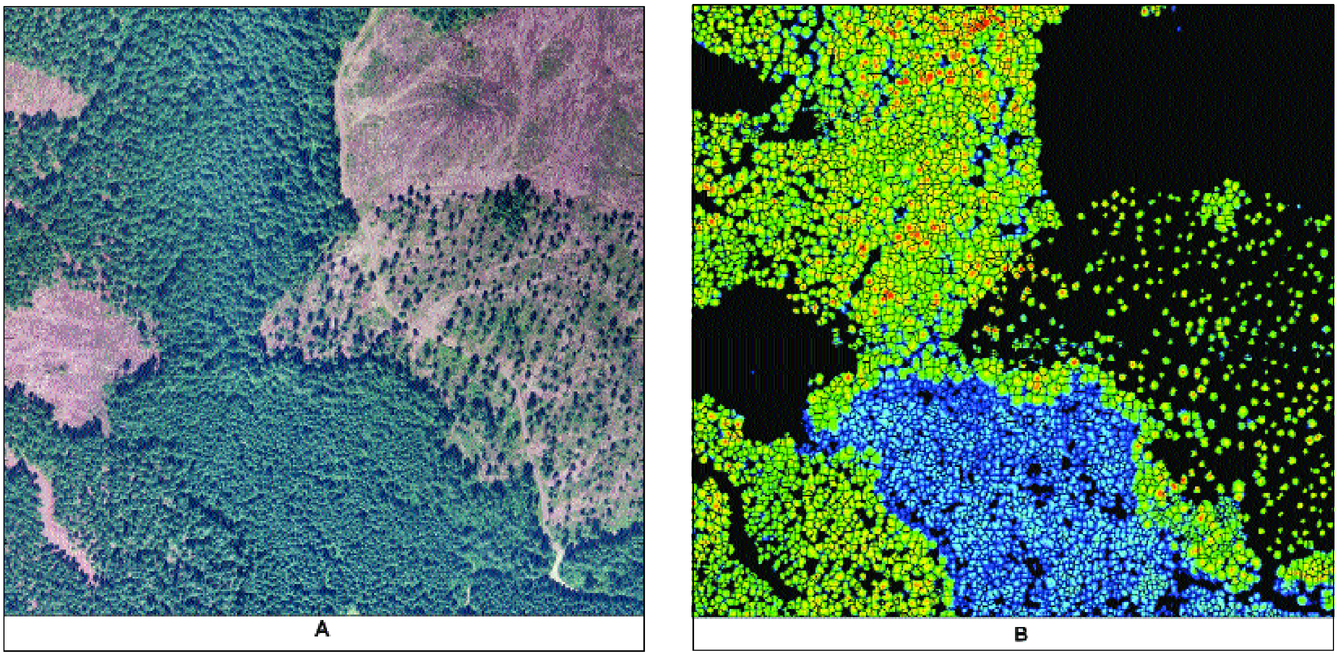


Figure 10—a) Orthophoto of selected area, and b) individual tree-level segmentation of LIDAR canopy height model via morphological watershed algorithm (color-coded by height; black lines indicate boundaries of segments).

measured by using a software system (FUSION) that provides for interactive visualization and direct measurement of the raw LIDAR point cloud (McGaughey et al. 2004). In fact, results from this study indicate that in open stands, individual tree dimensions (especially crown width and crown height) can be measured more accurately with LIDAR than with traditional field methods (by using Criterion laser instruments, etc.). LIDAR-based individual tree measurement can be automated through the application of computer vision algorithms. One of the more effective computer vision algorithms for automated individual tree crown recognition is the morphological watershed algorithm (Soille 1999). Conceptually, this algorithm finds the boundaries of b a s i n s , or watersheds, within a surface model. If the LIDAR- based canopy surface model is inverted, each tree crown is essentially a small basin, and after application of the watershed algorithm, the boundary of each individual tree crown is delineated. The output of this algorithm is a segmented canopy-height model, where each segment represents the area associated with individual tree crowns (fig. 10). A limitation of this LIDAR individual-tree level measurement approach is that only trees in the overstory can be accurately segmented and measured. However, in practice this is not a serious limitation because overstory trees are typically of most interest in the context of commercial forest inventory. Several previous studies have shown that this morphological computer-vision approach can be effective in identifying tree crown structures and measuring individual tree crown dimensions (Andersen et al. 2001, Persson et al. 2002, Schardt et al. 2002). Once the canopy height model has been segmented into individual tree crowns, the raw LIDAR data within each crown segment can be extracted to acquire high-resolution measurements of individual tree crown attributes, including tree height and crown base height (fig. 11). If height-to- diameter or crown-diameter-to-stem-diameter regression models are available for the area, these LIDAR-derived crown measurements can be used to estimate other tree attributes, including diameter and stem volume. In addition, because the near-infrared reflectance from hardwood crowns is significantly lower than conifers in leaf-off LIDAR data, the mean (or median) intensity of the LIDAR returns within each crown segment can be used to classify the tree segment into a species type (i.e., hardwood or softwood) (fig. 12).

LIDAR-BASED FOREST MONITORING

Measurement of Individual Tree Growth

When high-density LIDAR data are acquired over the same forest area in different years, the difference in the individual tree height measurements acquired from these multi-temporal LIDAR data sets represents an estimate of the tree height growth over the intervening period. This approach allows for accurate measurement of overstory tree

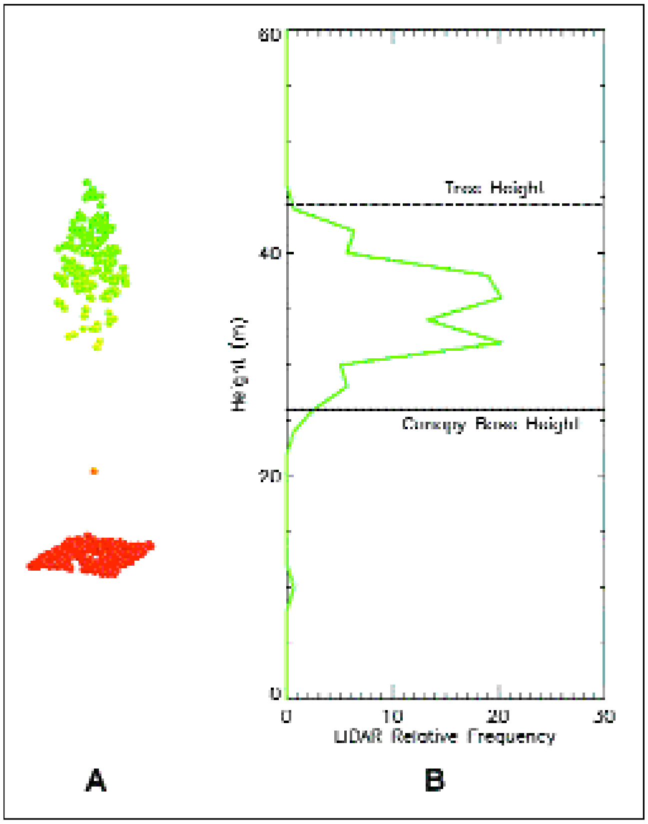


Figure 11—Use of LIDAR to measure individual tree crown dimensions: a) raw LIDAR measurements extracted from tree crown segment, and b) vertical distribution of LIDAR returns for this crown, with estimate of tree height and crown base height shown.

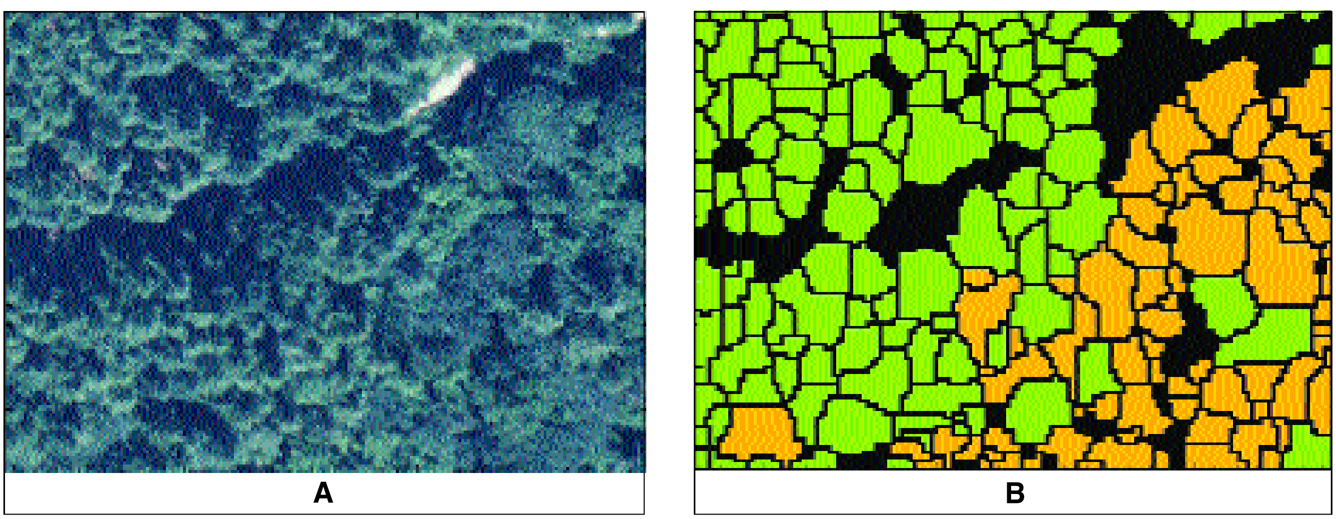
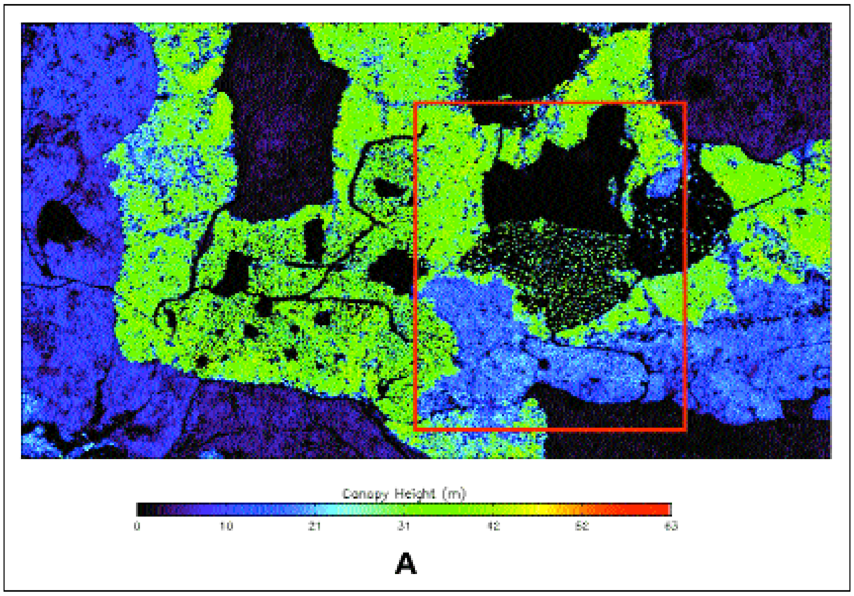


Figure 12—Use of LIDAR intensity to classify species: a) orthophoto of selected area with mixed hardwoods (bigleaf maple), and conifers, and (b) individual tree crown segments classified by species: conifer (green) and hardwoods (brown).



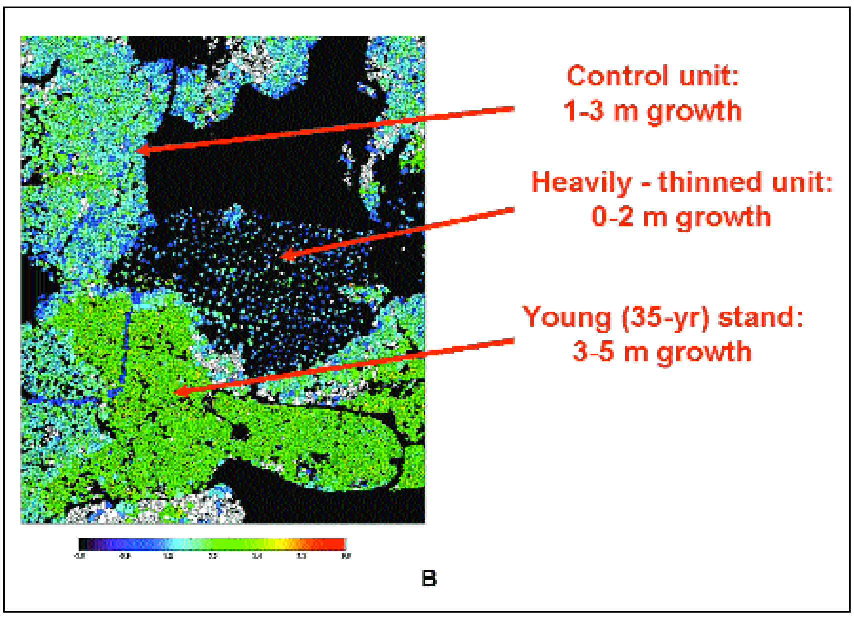


Figure 13—LIDAR-based measurement of individual tree growth, 1999-2003: a) Selected area within Capitol Forest study area shown in LIDAR canopy height model, and b) LIDAR-derived individual tree height growth measurement. A significant difference in height growth between stands is evident [control (70-yr.-old, unthinned stand) ~ 1- to 3-m growth; young (35-yr-old) stand ~ 3 to 5 m; heavily-thinned (70-yr-old stand)~ 0 to 2 m]. Segments colored white indicate hardwoods that were excluded from the analysis.

height growth over an extensive forest area. In a study conducted at the Capitol Forest study area, high-density LIDAR data acquired in 1999 and 2003 were used to extract individual tree height growth measurements. Preliminary results of this analysis showed that small differences in growth between thinning treatments can be detected even over this relatively short period (five growing seasons). As expected, height growth was less pronounced in the heavily-thinned unit (approximately 0 to 2 m), where the primary response to the treatment was increased crown expansion, than in the control unit, where the height growth was in the range of 1 to 3 m (fig. 13). Not surprisingly, the height growth within a younger (35-yr-old) stand was much higher (3 to 5 m) than in the mature stands. The capability of LIDAR to accurately measure the growth rates of individual trees across an entire forest provides an opportunity for much more detailed, and spatially explicit, analyses of site quality and availability, and intertree competition.

CONCLUSIONS

The application of airborne laser scanning to forest survey has the potential to revolutionize our approach to forest inventory and monitoring. LIDAR can provide very accurate measurements of terrain even under dense forest canopy (in both leaf-on and leaf-off conditions), and will support the implementation of more detailed hydrological models and site-specific forest operations. LIDAR also provides highly accurate, high-resolution measurements of forest canopy structure that can be used to estimate important inventory parameters at the plot level (dominant height, basal area, stem volume, biomass) and individual-tree level (height, crown area, crown base height). In addition, the intensity information provided by LIDAR can be used to classify forest species type, an important capability where information regarding forest composition, particularly hardwood-softwood mix, is required. It was also shown that the use of LIDAR data acquired in different years allows for forest-wide analysis of growth at the scale of the individual tree, which can potentially support highly detailed investigations of spatially variable site characteristics and growth potential. Through the analysis of LIDAR data collected before areas are cleared for plot establishment, differences in local site index across plots in the same block could be identified and accounted for in long-term plantation growth-and-yield studies, thus removing a potentially confounding effect that has been impossible to identify in most forest experiments.

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