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Measuring heights to crown base and crown median with LiDAR in a mature, even-aged loblolly pine stand

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ABSTRACT

This study evaluated the possibility of measuring the height to the base of the live crown and the height to the median of canopy elements with airborne scanning LiDAR (Light Detection And Ranging) in a simple, even-aged stand of loblolly pine. The first step in determining these heights was fitting truncated Weibull functions to the vertical distribution of elevations where discrete laser pulses were reflected from the dominant canopy strata. The height to the canopy median was defined as height at the median of the distribution. The height to the base of the live crown was defined as the height where the upper tail the distribution asymptotes to zero returns. Ground-based and LiDAR-based estimates of the canopy median differed by 0.3 m and were not significantly different ($P = 0.23$). Ground- and LiDAR-based estimates of the base of the live crown differed by 0.6 m and were significantly different ($P = 0.03$). LiDAR-based estimates of the canopy median exhibited positive bias over most of the range of field-measured values. Analyses of the LiDAR data resulted in overestimating the height to the canopy base over most of the range in field-measured values; however, the difference between ground and LiDAR-based estimates were negatively correlated with ground-based measurements. Average tree diameter was calculated with LiDAR-generated heights to the canopy median and to the base of the live crown. The overall average diameter was not statistically different from the overall quadratic mean diameter measured on the ground, demonstrating the possible utility of these canopy variables to forest managers working with simple stands such as plantations.

1. Introduction

Stand structure determines many attributes of forest stands and the individual trees within stands; the distribution of crown elements is a key component of stand structure. Distribution of crown elements affects canopy photosynthesis through its effects on light penetration and absorption (Monsi and Saeki, 2005; Wang and Jarvis, 1990; Stenberg et al., 1994). Tree properties such as stem taper and sapwood taper are influenced by the distribution of crown elements (Larson, 1963; Dean and Long, 1986a; Jokela et al., 1989; Dean et al., 2002). Distribution of canopy elements is also a major component of habitat diversity. MacArthur and MacArthur (1961) is noted for relating bird diversity with vertical diversity. Subsequent studies have demonstrated various effects of vertical structure on plants and animals in the forest (Brokaw and Lent, 1999).

Airborne laser scanning or LiDAR (Light Detection And Ranging) is an active remote sensing technique that has the potential to measure the vertical distribution of canopy elements (mostly branches and leaves) directly over large areas. Various approaches have been used to characterize forest structure with LiDAR. According to Lim et al. (2003), Arp et al. (1982) was among the first to characterize forest structure with lasers. The initial attempts in characterizing forest structure used a laser altimeter mounted on a fixed-wing aircraft that emitted discrete laser pulses (904 nm wavelength) at 4 kHz. Since the direction of the laser pulses was fixed, this technique produced a profile of canopy heights along the aircraft's flight line (Ritchie et al., 1993). This system recorded the first reflection from the vegetation or ground. Technical advances allow the energy reflected from the surface to be recorded in 10–30-cm height increments, producing a nearly continuous trace of reflected energy with elevation. The waveform produced by these systems corresponds well with the vertical distribution of canopy elements (Lefsky et al., 1999; Harding et al., 2001; Drake et al., 2002). The vertical distribution of canopy elements determines the vertical attenuation of solar radiation, and Parker et al. (2001) successfully used a waveform LiDAR system to account for the vertical distribution of photosynthetically active radiation (400–700 nm) of various forest types.

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While waveform LiDAR systems provide the most detailed information for characterizing the vertical distribution of canopy elements within a forest, the most common systems available commercially record discrete returns. In contrast to a wave pattern of reflected energy with height, the data created with discrete systems produce three-dimensional data clouds of horizontally referenced elevation or ''z'' values. Studies have related various stand and individual-tree characteristics to statistical metrics of the vertical distribution of the z values (Andersen et al., 2005; Hall et al., 2005). The limitations of calculating tree and stand properties from other variables are well known, and attempts have been made to measure various properties directly from the z values. The two most common variables recovered from the spatial pattern of z values are height and tree counts by measuring the heights and numbers of peaks in the data cloud (Næsset, 2002; Popescu et al., 2002; McCombs et al., 2003; Roberts et al., 2005). When analyzed in three dimensions, the upper surface of the cloud of z values resembles a dome, and both Popescu et al. (2003) and Roberts et al. (2005) attempted to measure crown diameter by measuring the width of the widest point of the dome. Roberts et al. (2005) also equated the point where two adjacent crowns touched as the midpoint of the crown. These studies indicate that direct measurements of vertical dimensions of trees is much more accurate than the horizontal dimensions, probably because vertical positions such as height and the center of the crown are more clearly defined than crown diameter. Crown diameter is more a function of the observer's mental image of arcs connecting groups of branches in the context of the general outline of the crown than a simple distance between opposite edges of the crown.

Vertical dimensions of individual tree crowns and of the forest canopy represent stand condition and are useful in stand management. Height at a particular age is a long-standing index of site quality. The length of the live crown relative to tree height is a useful indicator of competition and tree vigor (Kraft, 1884 as cited by Daniel et al., 1979). The height to the point in the crown that divides foliage area or mass equally (the median) is related to individual tree leaf area (Long et al., 1981; Dean and Long, 1986b) and stem diameter (Dean and Long, 1986a). Consequently, the ability to measure live-crown length, the height to the center of foliage area or mass, and live-crown ratio remotely and quickly over large areas would be of great utility in investigating and managing stand development and growth.

Profile views of z values correspond with the vertical distribution of biomass density, motivating attempts to quantify forest stand structure from the vertical distribution of z values. Multiple, linear regression has identified various quantiles and moments of the vertical distribution of z values that explain a large percentage of the variation in canopy properties such as the mean height to the base of the live crown or mean relative crown length (Næsset and Økland, 2002; Riano et al., 2004; Andersen et al., 2005). One of the problems encountered with statistical methods is the inter-stand variation in the signal-to-noise ratio; the signal being the returns from the canopy, and the noise being the returns from tree stems and understory vegetation. Holmgren and Persson (2004) approached this problem by assigning values of 0 or 1 to 0.5 m tall segments boundary by the outline of the tree crown according to the relative frequency of z values within a column of segments. Zero was assigned to segments containing less than 1% of the total returns from a tree originated in that segment. The base of the crown was the highest segment with a value of 0. Such a discrete classification of space can be thought of as volume elements or ''voxels'', which are analogous to ''pixels'' for discrete picture elements (Lefsky et al., 1999). Popescu and Zhao (2008) created a space of 0.5 m × 0.5 m × 1.0 m-voxels with the relative frequency of returns and relative intensity values within a column of voxels as attributes. The base of the live crown of various tree species in eastern Texas was then determined from the inflection points of 4th-degree polynomial fit through the values.

Theoretically, the spatial distribution of z values is an index of the probability of encountering a gap within the canopy (Ni-Meister et al., 2001). Coops et al. (2007) used this line of reasoning in using discrete LiDAR data to describe the vertical foliage profile of Douglas-fir (*Pseudotsuga menziesii* spp. *menziesii* (Mirb.) Franco). Two-parameter Weibull distributions were fit to the probability of encountering a gap calculated from the vertical distribution of z values and were compared to the distributions of the foliage as predicted from tree dimensions. Good agreement was found between the distributions. Furthermore, Coops et al. (2007) successfully predicted mean crown length from the scaling parameter c of the Weibull function. The objective of this study is to evaluate the potential for measuring the height to the canopy median and height to the base of the canopy with a modified voxel approach. The horizontal extent of an individual voxel is the area of a sample plot. The vertical dimension of each voxel is determined by the maximum height of the stand and the desired precision of height values. Two attributes are assigned to the voxels: relative height from the top of the plot and relative return frequency. Weibull functions fit to these attributes served two purposes: (1) identify voxels within the main canopy and (2) locate the heights to the canopy median and canopy base within a sample plot. The technique is evaluated by comparing these heights with field-measured values in a single-species, even-age stand of naturally regenerated loblolly pine (*Pinus taeda* L.).

2. Methods

2.1. Site description and field measurements

The study was conducted at H.G. Lee Memorial Forest, located in southeastern Louisiana near the city of Pine in Washington Parish, within a 36-year-old, naturally regenerated stand of nearly pure loblolly pine on gently rolling terrain. This stand had been thinned 8 years prior to this study and burned with prescribed fire every 1–2 years for 6 years prior to the study.

The study was conducted in conjunction with the pretreatment measurements of the Cooperative Research in Sustainable Silviculture and Soil Productivity (c.f. Carter et al., 2006) in installing studies of the effect of harvesting disturbance and site preparation on long-term productivity. These measurements include a complete inventory of the overstory vegetation in the experimental plots and a destructive analysis of the selected trees across the study site. Four such studies have been installed in Louisiana, one in Texas, and one in Georgia. Characteristics of plots established on this site are shown in Table 1.

The study site was divided into three replicates or blocks based on aspect and terrain. Eight, 28-m × 52-m plots were established on each block, not all contiguously. Stem diameter of every tree in the plot that was larger than 5 cm was measured at breast height (dbh, 1.37 m aboveground level). Height to the top of every tree was also measured, as well as height to the general base of the live crown. Height to base of the live crown was not the point of the lowest live branch; it was the height where the main crown began. A total of 786 overstory trees were measured on the 24 plots; 605 of those trees were loblolly pine. In addition to the plot measurements, during August and September 2002, 17 loblolly pine trees (~6 from each block) representing the range of tree sizes located at the site were severed near ground level to sample the vertical distribution of foliage and branch mass of trees in these plots. Foliage and branch mass were determined for 1-m sections

Table 1
Characteristics of the plots established within a 36-year-old loblolly stand at Lee Memorial Forest

Variable	Block	Mean	Minimum	Maximum
Trees (per ha)				
	A	163	110	234
	B	170	110	268
	C	340	234	419
Basal area (m^2/ha)				
	A	15.1	12.0	18.0
	B	15.6	10.3	20.0
	C	19.3	16.0	23.6
% BA in loblolly pine[a]				
	A	97.6	92.3	100
	B	99.0	92.6	100
	C	85.4	72.3	91.7
Dq (cm)[b]				
	A	34.9	29.3	38.0
	B	34.4	30.2	36.2
	C	27.1	24.7	30.6
Site height[c] (m)				
	A	25.7	25.3	26.0
	B	25.6	24.9	26.3
	C	25.7	25.1	26.4
Maximum tree height (m)				
	A	28.5	27.1	30.8
	B	27.7	25.6	29.0
	C	28.0	26.1	29.6

Plot means averaged by block ($n = 8$).
[a] Proportion of basal area in loblolly pine in percent.
[b] Quadratic mean diameter.
[c] Average height of trees taller than the median height.

in the crown following the procedures described by Dean et al. (2002). Sample trees ranged in total height from 21.9 m to 30.8 m, and in dbh from 24.4 to 57.4 cm. Jerez et al. (2005) included these data in evaluating how well Johnson's S_B probability density function described the vertical distribution of leaf area in loblolly pine of various age and subject to various treatments.

2.2. LiDAR data

LiDAR data were collected 28 June 2002 using an Optech ALTM-1225 operating at 25 kHz and a scanning angle of $\pm 9^\circ$. The aircraft flew at an altitude of 610 m at 62 m/s resulting in a minimum LiDAR posting density 4 laser pulses/m^2 and a swath width of 189 m. While the survey record from the vendor stated that flight lines were spaced for continuous coverage with no overlap between swaths, considerable overlap was apparent in two-dimensional maps of the returns. Horizontal position, height above local standardized height (the z value), and intensity were recorded for the first and last return of each outgoing pulse and were provided by the vendor in text files labeled according to flight line and origin of the return (ground or vegetation). Intensity values were not used in this study. Both vegetation and ground returns that originated from the plots that were established for the productivity study were extracted from the data. The z values of the vegetation returns were converted to height above the ground surface by subtracting the ground elevation from the vegetation elevation for each position via surface grids created for the vegetation and ground data. The surface grids were calculated using linear interpolation between z values. The minimum horizontal distance between z values was approximately 100 mm; therefore, grid size was set to 70 mm to minimize the chance of interpolation across z values. All subsequent analysis was conducted with the elevation-corrected, gridded data. For each plot, z values were grouped into 40 elevation classes relative to the maximum z value recorded on the plot. This number of classes combined with a maximum tree height of 28.5 m (Table 1) produces a vertical resolution of approximately 0.7 m. No analysis was performed on the effect of the number of classes and the precision of estimating the height to the base of the canopy or to the canopy median. The data fit to the Weibull functions were the relative return frequencies within the 40 elevation classes for each plot.

2.3. Heights to crown base and crown median

2.3.1. LiDAR data

Let x be the relative distance from the maximum z value (z_{max}): $x = 1 - (z/z_{max})$, $0 \le x \le 1$. A two-parameter Weibull probability density function was fit to the x values for each plot:

$$f(x) = \left(\frac{c}{b}\right)\left(\frac{x}{b}\right)^{c-1}\exp\left[-\left(\frac{x}{b}\right)^{c}\right] \quad (1)$$

where b and c are scale and shape parameters, respectively. The relative frequency of LiDAR returns will never approach zero below the canopy due to reflections from the stem and lesser vegetation (Fig. 1). In addition, at the base of the crown, the origin of the z values become confounded with the stem and midstory vegetation. The Weibull parameters b and c were thus estimated based on the right-truncated form of the Weibull function, i.e.,

$$f_T(x) = \frac{(c/b)\,(x/b)^{c-1}\exp[-(x/b)^{c}]}{1-\exp[-(t/b)^{c}]}, \quad 0 < x < t \quad (2)$$

where t = truncation. The value of t was determined by fitting a series of regression lines through successive groups of four data points moving right, starting from the mode of the value of x. When the slope of the regression fell below 0.1, the truncation point was set to the middle of the last two elevation classes in the group. The value of t does not correspond to the base of the canopy but was assumed to represent the lowest return that could be reliably attributed to reflections from the canopy.

Maximum likelihood estimates for the scale (b) and shape (c) parameters for the Weibull models were obtained for each plot by

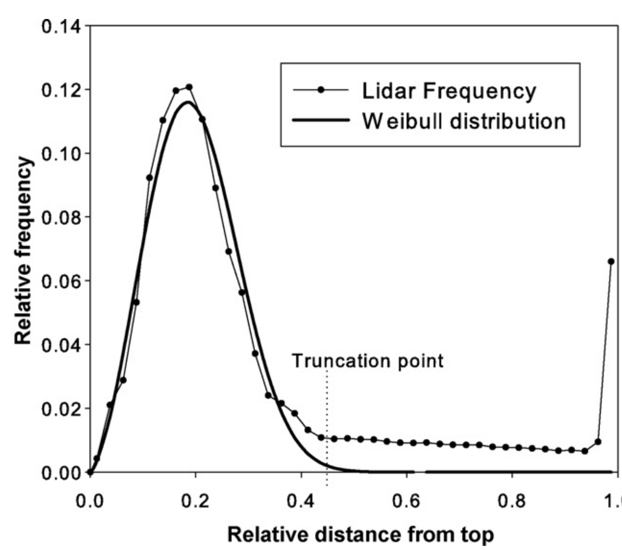

Fig. 1. Distribution of the LiDAR relative frequency and the Weibull distribution that approximates it. The LiDAR frequency was scaled such that the area under its curve from the tip to the truncation point is 1.

maximizing the following log-likelihood function:

$$\ln(L) = n\ln(c) - nc\ln(b) + (c-1)\sum \ln(x_i) - b^{-c}\sum x_i^c - n\ln\left\{1 - \exp\left[-\left(\frac{t}{b}\right)^c\right]\right\} \quad (3)$$

where x_i is relative distance of the ith z value return from the maximum value of z in that plot, and $\ln(x)$ is the natural logarithm of x. The summation sign includes values of i ranging from 1 to n, where n is the number of x values that satisfy $x < t$. Eqs. (2) and (3) serve only to estimate b and c; all subsequent analyses are performed with Eq. (1). The median value (M_x) of the Weibull distribution of x values was calculated for each plot using the equation

$$M_x = b(\ln 2)^{1/c} \quad (4)$$

Let x_{max} be the relative canopy depth (relative height from the tree top), which can be predicted as $\hat{x}_{max}$ from the Weibull distribution. Technically, $\hat{x}_{max}$ does not exist because the Weibull function theoretically extends to infinity (Fig. 1). From a practical standpoint, however, the number of returns from within the canopy predicted with the Weibull function is effectively zero at some maximum distance from the top of the tree. This effective value of $\hat{x}_{max}$ was determined by arbitrarily setting it equal to x such that $\Pr(X > x) = 0.00001$. The height to the base of the canopy is the product of $(1 - \hat{x}_{max})$ and z_{max}.

2.3.2. Field measurements

The height to the canopy base estimated from the LiDAR data is defined as the product of $(1 - \hat{x}_{max})$ and z_{max}. In single-storied stands, this value corresponds to the minimum height to the base of the live crown within a plot. Some plots had significant hardwood midstories, however, creating a bimodal distribution in heights to the base of the live crown (Fig. 2). In those plots, the height to the canopy base was defined as the minimum of the distribution of heights to the crown bases of the upper most strata.

The LiDAR estimate of the height to the canopy median is partly a function of the two extreme z values of the upper canopy strata. Analogous field estimates of the height to the canopy median are approximately the midpoint between the height of the tallest tree on a plot and the minimum height to the base of the live crown for the main canopy. Previous studies have determined that the midpoint of the crown separates foliage area into equal halves (Dean and Long, 1986a; Dean et al., 2002). Based on the analysis of Jerez et al. (2005) the relative crown position corresponding to the canopy median in these trees is 0.47 from the top of the tree (with 1 = canopy base). Therefore, the height to the crown median of the plots is the height difference between the tallest tree in the plot and the minimum height to the base of the live crown in the main canopy multiplied by 0.53.

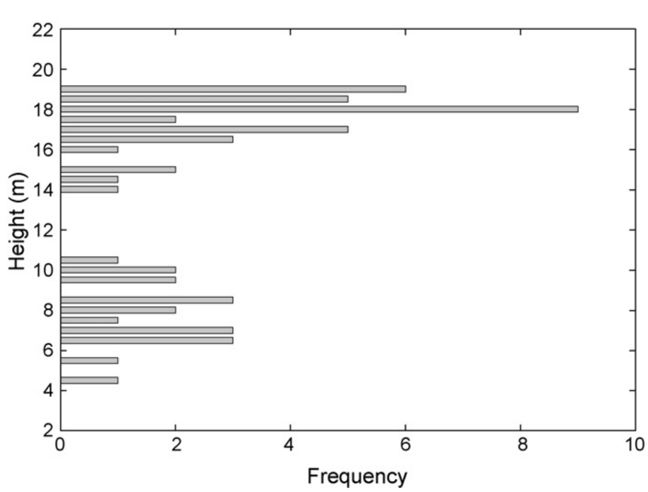

Fig. 2. Distribution of heights to the base of the live crown within a plot, illustrating the effect of understory vegetation on the distribution.

3. Results

The Weibull model fits the relative frequency distribution of x values well (Fig. 3). The flexibility of the function is demonstrated by its accurate representation of both the ascending and descending portions of the relative frequency of x values as a function of relative tree height. Consequently, the function should accurately predict the relative frequency of x values from zero up to where the data were truncated.

With $\alpha = 0.10$, no block effect was detected for either field or LiDAR measurements of height to the canopy median or height to canopy base. In addition, no block effect was detected on any difference between heights determined from the fitted Weibull functions and heights determined from field measurements.

The overall mean height to the canopy median determined from the fitted Weibull distributions for these plots is 21.1 m above ground (Fig. 4). The mean height to the canopy median determined from ground measurements is 20.8 m above ground. The null hypothesis that these two values are equal was tested with a paired t test and could not be rejected with this design and sample ($P = 0.23$).

The mean height to the canopy base determined for these plots with the fitted Weibull functions is 13.3 m above ground (Fig. 4). This value is 0.6 m higher than the value determined from ground measurements. A paired t test indicated that the sample was sufficient to reject the null hypothesis that these two means were equal ($P = 0.03$).

While the mean differences between LiDAR and ground-based estimates of vertical canopy dimensions are relatively quite small, they are biased with the corresponding ground estimate. The heights to the canopy median determined from the fitted Weibull functions are about 0.5 m above the ground-based estimate of the median up to approximately 21 m above ground (Fig. 5a). Between 21 and 22 m, Weibull and ground-based estimates are nearly identical, and above 22 m, Weibull estimates are below the ground-based values. The difference between Weibull and ground-based estimates of the height to the base of the live crown is strongly related to the corresponding ground-based measurements (Fig. 5b). The values derived from the fitted Weibull equations exceed the ground measurements of the height to the base of the live crown by more than 2 m when the crown base is 10–11 m above the ground, decreasing linearly with increasing ground-based heights, and eventually underestimating height to the canopy base by as much as 0.9 m. As with height to the canopy median, the majority of the Weibull estimates are higher than the corresponding ground measurements.

4. Discussion

The Weibull function has been used to describe vertical foliage distribution in trees for a number of species (e.g., Gillespie et al., 1994; Baldwin et al., 1997; Maguire and Bennett, 1996; Xu and Harrington, 1998). Since 80–90% of branch surface area is masked by foliage (Kucharik et al., 1999) and given the correspondence between z values and leaf area per unit ground area in even-age Douglas-fir stands (Magnussen and Boudewyn, 1998), a Weibull function is an appropriate choice for mathematically describing the vertical distribution of z values, at least in single-story canopies. Coops et al. (2007) came to the same conclusion.

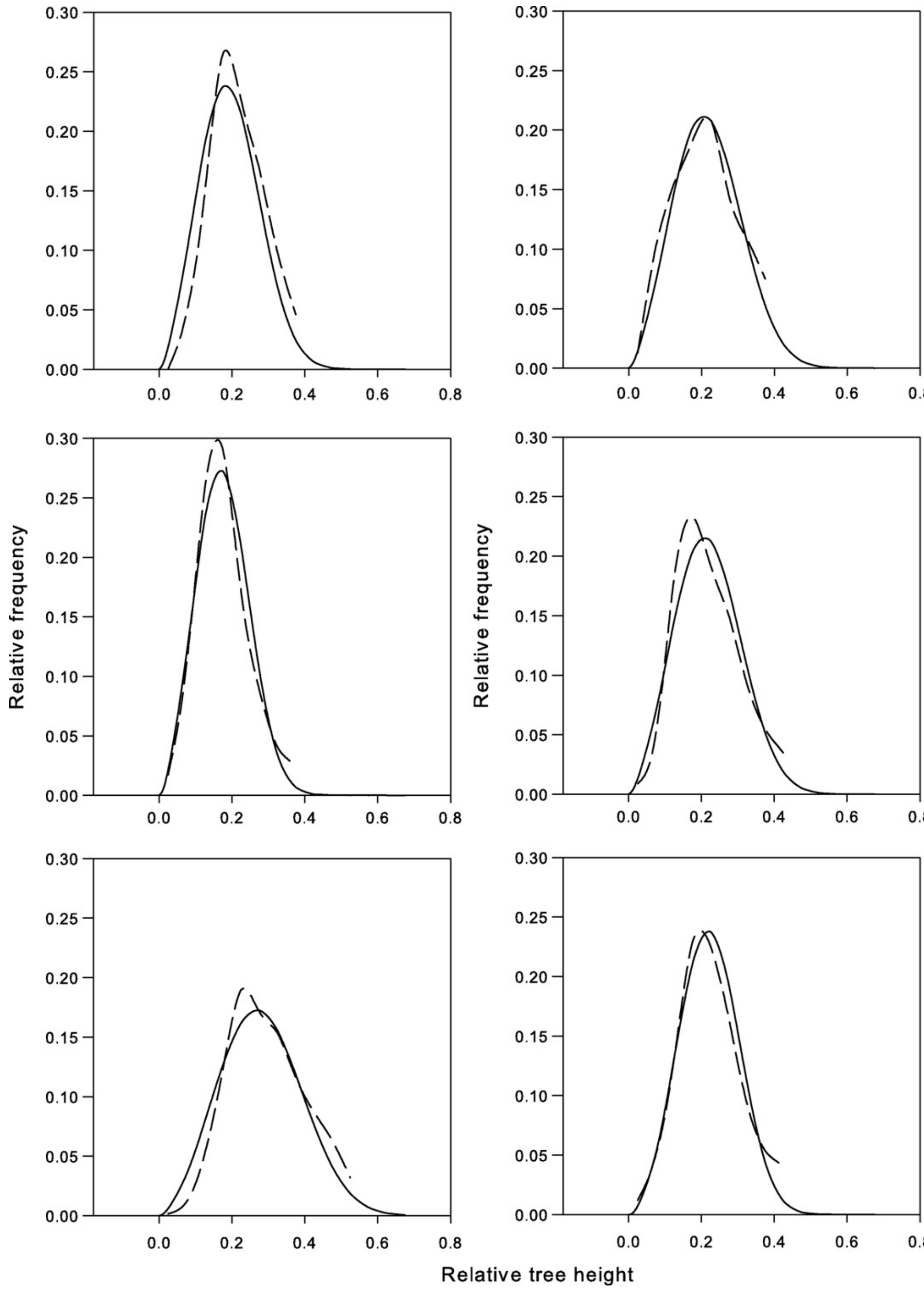

Fig. 3. Comparison of fitted Weibull function (solid line) to the distribution of z values from discrete LiDAR (dashed line) in the upper canopies of a 36-year-old loblolly pine stand near Pine, Louisiana.

Though not significantly different from the mean of the field-measured values, heights determined from fitted Weibull functions consistently overestimated height to canopy median for nearly half the range of ground-measured median heights (Fig. 5a). Jerez et al. (2005) did not account for branch angle in calculating the relative crown position associated with the median of foliage distribution, which may partly account for LiDAR-based estimates of height to the canopy median exceeding ground-based estimates. Stenberg et al. (1994) have shown that when the vertical foliage distribution of slash pine foliage is adjusted for branch angle, the distribution shifts toward the top of the tree. In this situation, the median of the Weibull function may be more sensitive to variation in height to the canopy median than ground-based estimates.

The mean height to the base of the live crown determined from the fitted Weibull functions was significantly higher than the mean of the field-measured values, and the nature of the error was much different than that height to the canopy median. Whereas LiDAR-based estimates of height to the canopy median exhibited a

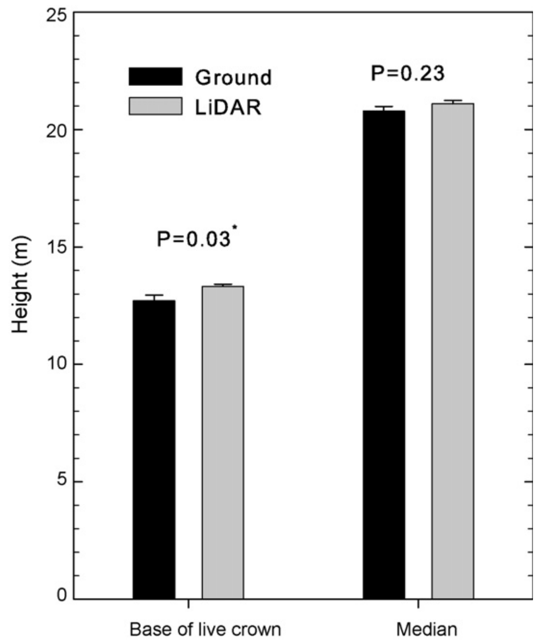

Fig. 4. Heights to the canopy base and canopy median determined from fitted Weibull functions and ground measurements. *P* values from paired *t* tests. Asterisk indicates use of the Cochran and Cox (1957) method of calculating the *t* statistic for samples with unequal variances.

constant bias for more than half the range of field-measured values, the difference between LiDAR-based and field-measured values of height to the canopy base was negatively correlated with the field-measured value (Fig. 5). For this study, the height to the canopy base does not appear to be directly estimable from discrete LiDAR data; however, the error between LiDAR and field-measured values found in this study is easily corrected with a linear equation developed with corresponding ground truthing data.

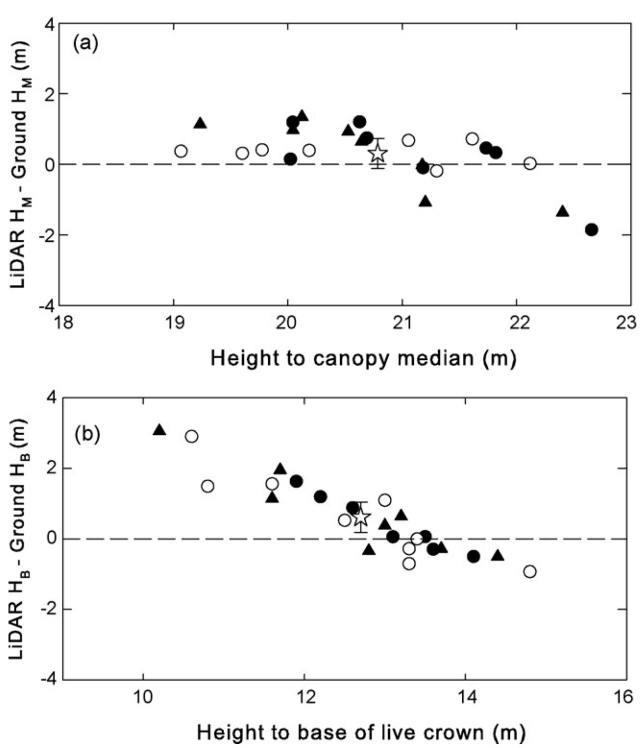

Fig. 5. Differences between Weibull-based and ground measurements of height to canopy median (a) and height to canopy base (b) for the upper strata of a 36-year-old loblolly pine stand near Pine, Louisiana. Star in figures locate the mean difference and the mean field value. Error bars extend to the upper and lower 95% confidence interval.

A positive bias in the LiDAR estimates of the height to the base of the live crown has been reported in several studies (Holmgren and Persson, 2004; Andersen et al., 2005; Coops et al., 2007). As canopy thickness is negatively correlated with height to the canopy base in this stand, the negative correlation of the estimation error and height to the base of the canopy manifests in the lower probability of the laser pulse finding a gap to the bottom of deep canopy. One means of overcoming such low probability of encountering a deep gap is recording multiple returns from a single pulse. Only the first and last returns per pulse were recorded with the LiDAR system used in this study; intermediate reflections from deeper in the canopy were not recorded. Later LiDAR systems are capable of recording multiple returns.

Deeper penetration of laser pulses into the canopy might also be possible by increasing the scanning angle of the pulses. Hosoi and Omasa (2007) evaluated the use of portable scanning LiDAR as point quadrats to measure the vertical distribution of leaf area within canopy of Japanese zelkova (*Zelkova serrata* (Thunberg) Makino) using methods developed by Warren Wilson (1960). Hosoi and Omasa (2006) conducted a similar study on isolated trees, In both studies, they scanned a section of the canopy or individual crowns with the instrument inclined at a various angles. They found that the indicated foliage profile varied with scanning angle. According to the theory of measuring leaf area distribution with inclined point quadrats, the distance a quadrat penetrates into the canopy is a combined function of the inclination of the quadrat and the orientation of the of the canopy elements. For the measurements made from the ground, the pulses inclined at approximately 45° penetrated furthest into the zelkova canopy. Pulses inclined at 40° from the horizontal penetrated the furthest into the crowns of individual trees. Since needles of loblolly pine have no preferential orientation, the average foliage angle could be considered to be 45°. For that case, a vertical beam of light has the least chance of penetrating the canopy (Anderson, 1966)—the maximum scan angle of the LiDAR system used in this study was 9°, almost vertical.

An example of the utility of heights to the canopy median and canopy base is the regression equation that calculates diameter at breast height from these height values:

$$\mathrm{dbh} = 0.234\, H_{\mathrm{BLC}}^{1.002} H_{\mathrm{M}}^{0.752} \quad (n = 17;\ R^2 = 0.97;\ \mathrm{s.e.}_{\cdot y} = 6.6\,\mathrm{cm}) \qquad (5)$$

where H_{BLC} = height to base of the live crown, and H_{M} = height to the crown median. Eq. (5) was fit to the destructively harvested trees selected from the study area. Dean and Long (1992) showed that a stand characteristic such as quadratic mean diameter could be calculated with a regression equation that had been developed with data from individual trees when the independent variables were also mean stand values. Calculating average plot diameters with Eq. (5) from H_{BLC} and H_{M} determined from the Weibull functions produced an overall mean diameter of 31.5 cm, which, according to a paired *t*-test, was not statistically different than the mean of the plot values of quadratic mean diameter, 32.1 cm, calculated from ground measurements ($P = 0.27$). The differences between the LiDAR estimates and direct measurements of quadratic mean diameter range from 7.5 to −6.6 cm and show no apparent bias with plot quadratic mean diameter (Fig. 6).

These results suggest that Weibull functions fit to gridded *z* values estimate the height to the canopy median directly with only a small and statistically insignificant positive bias. The height to the canopy base cannot be estimated directly from the fitted Weibull functions, probably due in part to the physical character-

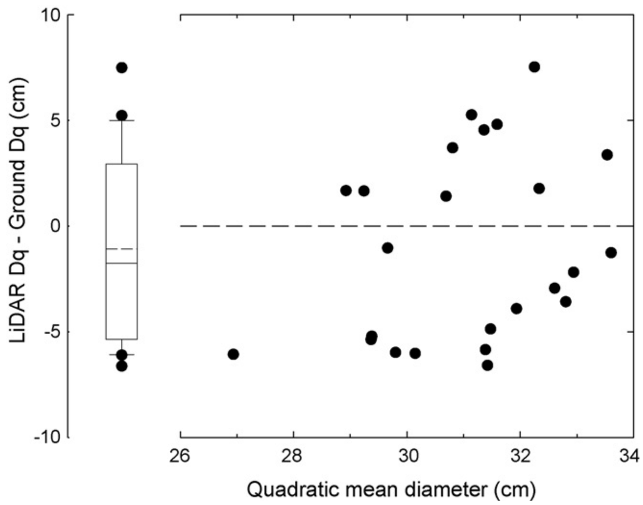

Fig. 6. Differences between LiDAR-derived estimates of average plot diameter and plot quadratic mean diameter. Box plot shows the mean and median difference (dotted and solid lines, respectively), 25 and 75 quartiles (lower and upper extent of box), and values outside the 5 and 95 percentiles.

istics of the LiDAR system used in this study. The error between LiDAR-based and field-measured values of height to the base of the canopy is linear with field-measured values, which could easily be corrected with ground measurements. Combined with improved methods for detecting individual trees and measuring their heights, the ability to determine average stand characteristics such as heights to the canopy median and to the base of the canopy create the potential to quantify several important characteristics for plantation managers without entering the stand. Stand volume can be calculated from estimates of quadratic mean diameter, mean tree height, and numbers of trees. Improved procedures for remotely measuring these variables will also improve estimates of canopy leaf area. Average live-crown ratio is indicative of average tree vigor and can be calculated from mean height and height to the base of the canopy. Given the speed and spatial extent with which LiDAR data can be collected, the ability to calculate basic stand characteristics quickly over a wide area may allow managers to prescribe treatments on a much shorter cycle than is economically feasible with ground crews.

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