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Investigating laser pulse penetration through a conifer canopy by integrating airborne and terrestrial lidar

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Abstract. This study examines the distribution of laser pulse returns obtained from coincident airborne and terrestrial lidar surveys of a closed-canopy red pine (*Pinus resinosa*) plantation. The purpose of this study is to improve our understanding of laser pulse sampling within closed canopies so that estimates of forest structural variables (e.g., biomass, needle-leaf area, and base-of-live-crown) can be improved at the individual tree and stand levels using lidar. The results of this study indicate the following: (1) There is a statistically significant difference between field measurements of tree height and estimates derived from the maximum laser pulse return from airborne and terrestrial lidar. In both cases, maximum laser pulse returns underestimate tree height by 1 m, on average. (2) Both terrestrial and airborne lidar are unable to discern the base of the measured live crown. Laser pulse returns from airborne lidar are biased towards the top of the tree crown, i.e., lowest laser pulse returns occur 1.4 m on average higher in the canopy than the measured base-of-live-crown. On the other hand, terrestrial lidar captures dieback at the base of the live crown, thereby lowering the base-of-live-crown estimate by 6.6 m, on average. (3) Median airborne laser pulse returns within the canopy (20.4 m), believed to be associated with needle leaf area, occur below the maximum frequency of laser pulse returns (20.8 m) but higher in the canopy than the height of maximum crown diameter obtained from terrestrial lidar (18.0 m). The bias of airborne laser pulse reflections towards the top of the canopy with less penetration to a depth where the maximum crown diameter occurs may result in an underestimation of the needle leaf area. The results of this research suggest that future research should focus on improving our understanding of how laser pulse returns are "triggered" within vegetated environments and how canopy properties or data acquisition parameters may influence the location of this "trigger" event.

Résumé. Cette étude examine la distribution des réflections d'impulsions laser dérivées au cours de levés parallèles à partir de plateformes aëroportée et terrestre d'un peuplement de pins rouges (*Pinus resinosa*) à couvert fermé. L'étude a pour objet de pousser plus loin notre compréension du prélèvementc d'échantillons par impulsion laser dans un environnement de couvert fermé, ceci afin de perfectionner nos estimations des variables structurelles forestières (par exemple: la biomasse, l'indice foliaire des aguilles de pin, et le fond de la couronne vivante) aux niveaux de l' arbre ou du peuplement individuels. Les résultats de l' étude donnnent à entendre que : (1) Il existe une différence statistiquement significative entre les mesures de la hauteur des arbres faites sur le terrain et les estimations de hauteur faites à partir des réflections maximales d'impulsions laser dérivées à partir de lidars aéroporté et terrestre. Dans tous les deux cas, les réflections maximales d'impulsions laser donnent un résultat qui sous-estime la hauteur des arbres d'environ un mètre en moyenne. (2) Ni le lidar aëroporté ni le terrestre ne distingue le fond de la couronne vivante mesurée. Les réflections d'impulsions laser à partir du lidar aéroporté sont biaisées vers la cime de la couronne forestière, c'est à dire que les réflections d'impulsions laser les plus profondes se produisent à un point en moyenne 1,4 m plus haut dans le couvert que le fond mesuré de la couronne vivante. En revanche, le lidar terrestre capte le dépérissement des rameaux au fond de la couronne vivante et, de ce fait, diminue la hauteur estimée du fond de la couronne vivante de 6,6 m en moyenne. (3) Les réflections médianes des impulsions laser provenant de l'intérieur du couvert forestier (20,4 m), et dont on croit que la valeur numérique serait associée à la surface foliaire des aiguilles de pin, se produisent à une hauteur inférieure au niveau de fréquence maximum des réflections laser mais supérieure à celle du niveau du plus grand diamètre de la couronne relevée par lidar terrestre (18,0 m). Cet effet de biais vers la cime du couvert forestier des réflections d'impulsion avec en même temps une plus faible pénétration vers le niveau où le diamètre de la couronne est au plus grand peut donner lieu à une sous-estimation de la superficie foliaire. Ces résultats suggèrent que les recherches futures devraient focaliser notre compréhension du processus de «déclenchement» des réflections d'impulsions laser en milieu végétalisé ainsi que notre compréhension de la mesure dans laquelle les propriétés du couvert ou les paramètres de l'acquisition des données peuvent influer sur la localisation de l'évènement déclencheur.

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Introduction

Airborne and terrestrial light detection and ranging (lidar) systems are increasingly being used for estimating vegetation structural variables such as tree height, base-of-live-crown, basal area, stem count, and radiation transmissivity. Vegetation biomass components (stems, branches, and foliage), understory, and ground are sampled in three dimensions using laser pulses that are rapidly emitted and received by the sensor optics. Both sensors work similarly to record the time between laser pulse emission and reception, thereby locating laser pulses within three-dimensional space. Airborne lidar, however, is more complicated because laser pulse returns must also be adjusted for the pitch, roll, and heading of the aircraft using an inertial measurement unit (IMU). Laser pulse returns are also referenced to a geographical coordinate system using global positioning systems (GPSs) on the ground and within the aircraft. Data streams are then combined using proprietary software processed by the lidar service provider. Airborne lidar is optimal for local to regional surveying of vegetated environments, whereas terrestrial lidar is more appropriate for detailed tree- and plot-level analysis. As a result, the use of lidar has become widespread within forested environments, and the methods used to extract vegetation structural variables have improved, thereby increasing the processing ease and accuracy of lidar-derived forest metrics (e.g., Naesset, 2002; Hopkinson et al., 2004).

Despite advances in lidar vegetation analysis, the sampling of laser pulse returns within forest canopies is not well understood. In some cases, forest metric estimation errors are not quantified because sampling of canopy structure (i.e., beyond tree height, base-of-live-crown, and leaf area index (LAI)) at the branch level is not conducted. Statistical approaches are often used to relate laser pulse return distributions to vegetation structure, but these approaches do not account for laser and canopy influences on the laser pulse return. Studies are progressing, however, towards the estimation of biomass and leaf area modelled from estimates of canopy height and openness derived from lidar data (e.g., Popescu et al., 2003; Lim and Treitz, 2004). Biomass, leaf area, and canopy clumping are important for energy exchanges within the canopy and the overall health and productivity of vegetation. Therefore a better understanding of the physical distribution and reflection properties of laser pulse returns within the canopy is required so that allometric equations and physical relationships between laser pulse return distributions and biomass can be assessed. Without a thorough analysis of the influences on and physical distribution of laser pulse returns within the canopy, there is the potential for systematic biases in the data and the forest metrics derived, thereby leading to errors in canopy characteristic models.

The understanding of the distribution of laser pulse returns within forested and vegetated environments can be improved by combining airborne and terrestrial lidar. For example, rapid sampling of vegetation using airborne and terrestrial lidar systems results in variations in the density of sampling between the two systems. Because laser pulse return density per tree varies between airborne and terrestrial lidar, both systems can be used separately to estimate structural characteristics of vegetation. Terrestrial lidar can also be used to validate the results of airborne lidar because the density of laser pulse returns is between two and three orders of magnitude greater than that from airborne lidar.

The following study examines a variety of questions related to the distribution of coincident airborne and terrestrial laser pulse returns within a closed red pine (*Pinus resinosa*) plot at both the individual tree level and plot level. The higher density of laser pulse returns from terrestrial lidar has been used, in part, to validate metric results of airborne lidar. These questions follow a review of the current state of knowledge in airborne and terrestrial lidar remote sensing of tree–forest canopies.

Research utilizing terrestrial and airborne lidar within forested environments has followed slightly different directions due to contrasting laser pulse sampling density and geometry. Airborne lidar is generally applied at local and regional scales for the purposes of resource monitoring and commercialization (e.g., Holmgren and Jonsson, 2004). The application of airborne lidar for satellite and ecosystem model validation (Lefsky et al., 2005) and understanding of physical processes related to biomass and canopy structure (Hopkinson et al., 2005) is becoming more common. The development of terrestrial lidar within forested environments has tended to focus on recreating structural elements within individual tree canopies (Gorte and Winterhalder, 2004) for modelling of physical processes at a variety of scales (e.g., Fleck et al., 2004) and forest inventory at permanent sample plots (Hopkinson et al., 2004; Thies and Spiecker, 2004).

The distribution of laser pulse returns for forest canopies and individual trees has been related to forest characteristics with varying levels of success. These include tree stem density and location (e.g., Naesset and Bjerknes, 2001; Koukoulas and Blackburn, 2005), mean tree height (e.g., Naesset and Bjerknes, 2001), basal area (e.g., Means et al., 2000; Naesset, 2002), biomass (e.g., Lim and Treitz, 2004), LAI (e.g., Magnussen and Boudewyn, 1998), and tree crown diameter (e.g., Popescu et al., 2003). At individual tree, branch, and leaf levels, terrestrial lidar has shown promise for rapid generation of mensuration statistics (Hopkinson et al., 2004). A number of studies have also focused on full reconstruction of tree elements, including tree stems for cross-section analysis (Pfeifer and Winterhalder, 2004), tree branches (e.g., Gorte and Winterhalder, 2004), and laser intensity based recognition of wood quality (Schutt et al., 2004). The high density of laser pulse returns and the detailed reconstruction of tree elements from terrestrial laser scanners have promoted more physical process based research on radiation and photosynthesis modelling that requires detailed structural information at a variety of scales and validation with localized energy exchanges. For example, Fleck et al. (2004) applied a three-dimensional light and photosynthesis model to leaf clouds generated using a Hough transform. Acclimation of leaf properties through the canopy was found to vary with canopy structure obtained from terrestrial lidar and modelled radiation penetration.

In open canopies, tree height estimates from airborne lidar accurately represent field-validated tree heights, with correlation coefficients (R^2) ranging from 0.90 to 0.99 (e.g., Magnussen and Boudewyn, 1998; Maltamo et al., 2004). Despite the increasing adoption of airborne and terrestrial lidar for forest research, laser pulse return distribution characteristics remain unquantified and poorly understood (Naesset, 2005). Airborne laser pulse sampling of the vertical canopy profile tends to improve when canopies are more open in nature because laser pulses will backscatter and "return" from the sides of trees, especially if individual trees are subject to pulses emitted from two directions (Magnussen and Boudewyn, 1998). However, forest metrics derived from airborne lidar systems become more difficult to extract from closed canopies because laser pulse returns tend to be preferentially distributed towards the outer envelope of the tree crown, with fewer pulses penetrating past the height above ground level at which canopies become closed (e.g., Lovell et al., 2003; Maltamo et al., 2004). This makes the estimation of the base-of-live-crown a variable that is useful for estimating biomass or "biovolume" and LAI particularly difficult while also reducing the effectiveness of determining peaks and valleys in the top of the canopy required for tree height and stem density (Popescu et al., 2003). Resulting laser pulse return densities within the upper parts of the canopy may also adversely affect the accuracy of radiation and photosynthesis models that depend on laser pulse sampled tree structure. Maltamo et al. (2004) also note difficulties in acquiring individual tree heights within overstory and understory canopies, especially as canopies become more closed.

Terrestrial lidar also tends to vary in penetration from the base of the tree crown (including dead and live branches) through to the top of the canopy and with depth into a forest stand. For example, Chasmer et al. (2004) assessed the distribution of laser pulses emitted from a terrestrial lidar within deciduous and conifer plots and found that laser pulse frequencies decreased with tree height such that laser pulses may or may not reflect from the highest point in the canopy. Hopkinson et al. (2004) used the same data and found that mean tree heights obtained from terrestrial lidar for 76 trees tended to underestimate red pine heights by 1.5 m. Further examination of the distribution of laser pulse returns from both airborne and terrestrial lidar sensors within forest canopies is required to improve our understanding of how these distributions represent the three-dimensional canopy environment.

In this study, terrestrial lidar data are used to assess the distribution of laser pulse returns collected from an airborne laser scanner for 15 trees in a closed-canopy red pine (*P. resinosa*) plantation. The following questions are addressed: (1) How do individual tree height estimates derived from airborne and terrestrial lidar data compare with manual measurements using standard field mensuration procedures? (2) How do individual tree base-of-live-crown estimates derived from airborne and terrestrial lidar data (lowest within canopy height) compare with manual field measurements, and how do these differences affect canopy depth estimates? (3) What, if any, relationship does the height of maximum crown width have with the distribution of airborne laser pulse returns through the canopy? It is expected that the answers to these questions will improve our understanding of laser pulse return sampling within closed canopies and in relation to forest structure and lidar-derived metrics.

Study area

The red pine plantation used in this study is located within a mixed forest approximately 50 km north of Toronto, Ontario, Canada. The plot varies in elevation by less than 1 m and contains no understory. Tree heights consistently fall in the range of 23–24 m. The minimum distance between two trees is 1.5 m, but is typically 2.0 m.

Data collection and processing

Airborne lidar

Airborne lidar data were collected on 5 July 2002 using an Optech Inc. (Toronto, Ont.) ALTM 2050 (50 kHz) discrete pulse return lidar. The sensor was flown at 850 m above ground level (agl) with 50% overlap of scan lines to ensure even pulse distributions on two sides of the tree canopy. Scan angles of laser pulse emission varied between 0 and 14°. First and last laser pulse return positions were calculated using POSPac (Applanix Inc., Toronto, Ont.) and REALM (Optech Inc.) software packages by combining laser pulse ranges and scan angles with the differentially corrected aircraft kinematic GPS trajectory and sensor attitude information from an IMU within the sensor head. Laser pulse returns were classified into ground and nonground returns within the TerraScan software suite (Terrasolid Ltd., Jyvaskyla, Finland). Laser pulse return density within the crown circumference of each tree varied between 28 and 43 returns within the canopy and between 16 and 22 returns at ground level.

Terrestrial lidar

Terrestrial lidar data were collected coincident with the airborne lidar survey on 5 July 2002 using an Optech Inc. tripod-mounted ILRIS-3D terrestrial lidar system. The ILRIS-3D has a horizontal and vertical field of view of 40° × 40°. Data were collected from five locations, with scan lines centering on a reference point within the homogeneous stand (Hopkinson et al., 2004). Distances from the locations of the scanner to individual trees varied from 15 to 60 m. The 15 trees used in this study were selected based on their proximity to a central reference point to maximize laser pulse density and to reduce the influence of "shadowing" due to obstructions in the foreground. The scanner was also tilted upwards at angles of 10°–20° to maximize penetration into the canopy. The total number of laser pulse returns for each tree varies from 4000 to

87 000, with 12 of the 15 trees having greater than 30 000 laser pulse returns. The trees used in this analysis, although varying in numbers of laser pulse returns, contain all major sections of the tree canopy with no visible gaps. Alignment of scans was performed in InnovMetric (Sainte-Foy, Que.) Polyworks software using the IMAlign module.

Field data collection

Field-validation data were collected during the period 4–17 July 2002. All trees were uniquely numbered with aluminium tags prior to measuring individual tree position, height, crown depth, crown diameter, and stem diameter at breast height (DBH). Tree heights and depths of crown for individual trees in the red pine plot were measured from the ground to the top of the live canopy and then to the base-of-live-crown using a Vertex sonic clinometer (Haglof, Madison, Miss.). Tree height measurements were taken at a distance approximating the vertical height of the tree. The base-of-live-crown was sometimes difficult to estimate because red pine are prone to senescence and dieback lower in the canopy, leading to partial live foliage. Therefore, base-of-live-crown height was measured to the live branches nearest to the ground surface. Individual tree stem DBH measurements were made at a height of 1.3 m above the ground using a DBH tape measure. Tree crown diameter was determined as the maximum of two measures along the cardinal directions (north–south and east–west) using a measuring tape and a compass.

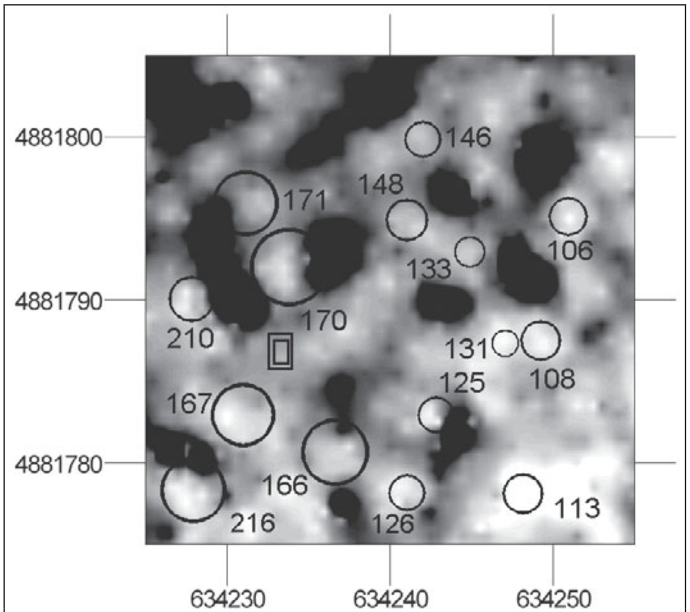

Figure 1. Canopy height model, tree locations, and proportional tree crown diameters based on the maximum (north to south and east to west) for 15 trees (open circles with numbers) used in this study. Other trees (not used in this analysis) are also visible in the canopy height model as variations in heights surrounding labelled trees. The *X* and *Y* axes represent Universal Transverse Mercator (UTM) coordinates of the study area. Also shown is the central point for which all ILRIS scans were referenced (double rectangle) and centred on from five different locations in the plot (Hopkinson et al., 2004).

Stem map

An inertial survey instrument known as the position orientation system – land survey (POS-LS) and manufactured by Applanix Inc. was used to locate trees within the plot. The POS-LS uses an IMU and a differential global positioning system (DGPS) receiver to obtain accurate positions of objects in three dimensions. The IMU is used to monitor movements of the operator through time. Using a known initialization point and survey-grade GPS, the POS-LS can be used to accurately survey tree stem locations beneath dense forest canopies (see Hopkinson et al., 2004). Following the stem map survey, the POS-LS was reinitialized on a known survey location (1 km west of the plot) so that any instrument drift could be compensated. Location errors were less than 5 cm as measured at the side of the tree stem.

Methodology

Lidar data processing

To enable direct comparison of the lidar data with field validation data, it was necessary to remove topographic height and variability from each laser pulse return coordinate. A digital elevation model (DEM) was created from the ground-classified laser pulse returns using an inverse distance weighting (IDW) algorithm and a search radius of 1.5 m within Surfer (Golden Software, Inc., Golden, Colo.). Residuals between the DEM and all laser pulse returns were used to determine the height of returns above or on the ground surface without topographical influence. Individual tree point clouds were obtained, in part, using the tree locations from the POS-LS. Tree crown centres, however, were shifted from the location of the stem on the ground due to prevailing winds (Popescu et al., 2003). To account for this shift and identify actual tree crown locations, a canopy height model (CHM) was created from the filtered local maximum height laser pulse returns using an IDW gridding algorithm (**Figure 1**). Tops of tree canopies were compared both in height and in location to field-sampled tree heights and locations obtained from the POS-LS data. Individual tree coordinates (i.e., for the 15 trees) were established based on the gridded maximum height and proximity to the nearest POS-LS tree location. Individual tree lidar point clouds were then extracted by selecting points within a specified radius from centre based on the maximum crown diameter (**Figure 1**). Additional trees also occur within the CHM (**Figure 1**) but were not examined due to poor stem and (or) canopy representation within the terrestrial lidar point cloud.

Statistical analysis

Terrestrial and airborne lidar top-of-live-crown has been defined as the highest recorded laser pulse return located above ground level within the circumference of the tree crown. Base-of-live-crown estimates for the airborne lidar data consist of the lowest laser pulse return within the tree crown, whereas the base of the tree crown is estimated at the lowest pulse return on the lowest branch for the terrestrial lidar data. Returns from branches at the base of the tree crown obtained from terrestrial lidar may be living or dead. The ability to differentiate live and dead base of the tree crown has not been examined here. The lowest branch obtained for individual trees using terrestrial lidar has been manually identified by visually inspecting the laser pulse return point cloud. Median airborne laser pulse height is the height at which the median laser pulse return occurs within the canopy (excluding ground surface pulse returns). A Student's *t* test is used to test the difference between field, terrestrial, and airborne observations based on the means of the sample (Ebdon, 1985).

Results and discussion

Comparison of tree heights

Tree heights obtained from airborne and terrestrial lidar are estimated as the maximum (highest) laser pulse return within the crown radius footprint. These are then compared with the field measurements of individual tree crown heights. The differences between airborne and terrestrial lidar maximum height of laser pulse returns and field-measured tree height for each of 15 trees are illustrated in **Figure 2**. The results of this analysis indicate that maximum laser pulse return height from airborne and terrestrial lidar underestimates field-measured tree height by an average of 1.1 m (standard deviation (sd) of 0.8 and 1.5 m for airborne and terrestrial lidar, respectively). Airborne and terrestrial lidar tree heights were significantly different ($P < 0.0001$) from field validation measurements. Magnussen and Boudewyn (1998) and Maltamo et al. (2004) also found similar discrepancies between airborne lidar estimated tree heights and those measured in the field. Penetration of airborne laser pulse returns into the canopy results in lower maximum laser pulse return heights and a lower estimated top-of-live-crown. This is likely due to the low probability of pulse returns from the apex of the crown (the point of field validation measurements) and also laser pulse penetration into the foliage before sufficient energy is backscattered to trigger a return within the sensor timing electronics (e.g., Gaveau and Hill, 2003). Similarly, Hopkinson et al. (2004) found differences between measured and terrestrial lidar-estimated tree heights (from maximum height of return within the canopy). This was largely due to reduced numbers of laser pulse returns within the upper canopy because of shadowing by branches and stems near the ground surface. These results illustrate that heights of individual red pine trees, as estimated from the within-crown radius maximum laser pulse return height, are typically underestimated using both airborne and terrestrial lidar sensors. The magnitude of height underestimation is similar but for different reasons.

Comparison of base-of-live-crown

Measured base-of-live-crown and the height of lowest laser pulse returns within the crown from both airborne and terrestrial lidar were compared. The ability to identify base-of-live-crown from lidar data has implications for biomass

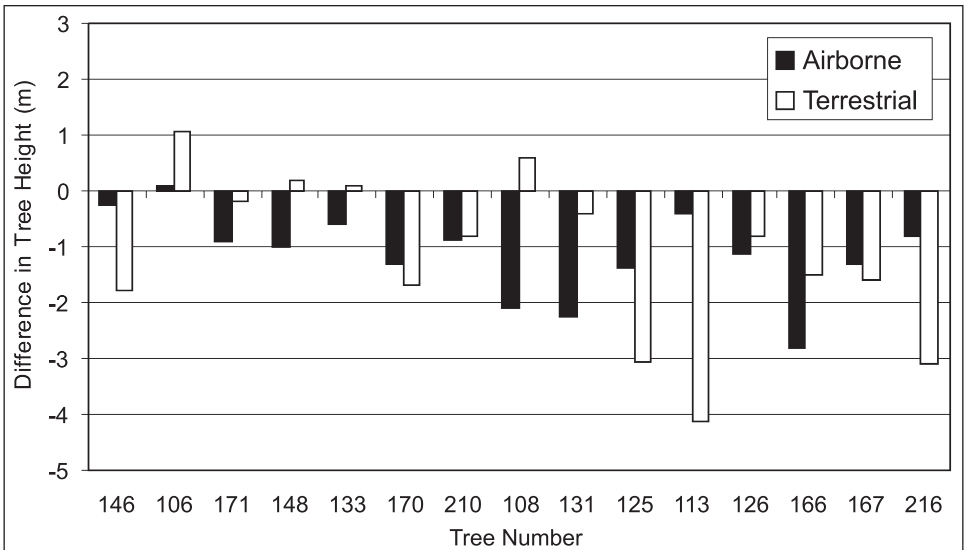

Figure 2. Differences in laser pulse maximum height returns for airborne and terrestrial lidar compared with field-measured top-of-live-crown (field height – lidar height). In most cases, airborne and terrestrial lidar underestimate the top-of-live-crown. For trees 106 and 108, top-of-live-crown estimated using the terrestrial lidar appears much higher than field-measured tree heights. This is likely due to field measurement error and an inability to see the crown apex. Incidentally, these two trees are the shortest in height of all trees measured and are outliers in the dataset.

estimation, radiation modelling, vegetation health, and carbon studies. Errors in lidar estimates of base-of-live-crown could detrimentally affect canopy depth based estimates of biomass, leaf area, radiation penetration, and leaf photosynthesis (e.g., Parker et al., 2001). A comparison of field measures and lidar estimates of base-of-live-crown is provided in **Figure 3**.

On average, the lowest within-canopy laser pulse returns from airborne lidar are approximately 1.4 m higher in the canopy than the measured "actual" average base-of-live-crown for the trees examined (sd = 2.4 m, $P < 0.01$). Terrestrial laser pulse returns reflect best from lower parts of the tree canopy, with lowest "apparent" base-of tree-crown returns being approximately 6 m below the field-measured base-of-live-crown (sd = 1.2 m) (**Figure 3**). For both airborne and terrestrial lidar data, the null hypothesis of no difference between lidar estimates and field measures of the base-of-live-crown in closed conifer canopies is rejected.

It was found, however, that airborne laser pulse returns occurred at lower depths for tree crowns that were located at greater distances from other trees (e.g., trees 133, 146, 166, 170, 171, and 210; see **Figure 1**). These trees were, on average, a distance of 5 m from adjacent trees (i.e., range of 2.9–6.4 m), exhibiting greater crown openings. Laser pulse returns from these trees penetrated 2.3 m farther into the crown, on average, than laser pulse returns from trees that were grouped within close proximity (i.e., <2 m). As a result, airborne laser pulse returns slightly overestimated the base-of-canopy for these trees by only 0.4 m. On the other hand, laser pulse returns for grouped trees overestimated the base-of-canopy by 2.7 m, on average. These results are significantly different at $P < 0.01$.

The depth of the crown and the foliage profile are important for understanding radiation penetration through the canopy and biomass characteristics. For the trees in this study, the average field-measured depth-of-crown was 9.5 m (sd = 1.0 m) compared with 7.0 m (sd = 1.6 m) using airborne lidar and 3.4 m (sd = 3.8 m) using terrestrial lidar. **Figure 4** illustrates the differences in laser pulse returns between airborne and terrestrial lidar point cloud data for comparison. Top-of-live-crown and base-of-live-crown measured in the field are compared with airborne and terrestrial lidar metrics. Crown depth estimates from field measurements are significantly different ($P < 0.0001$) from the laser pulse return distributions. The possible implications of these observations can be better appreciated if one considers the use of lidar point cloud data for driving radiation and photosynthesis models. If a terrestrial lidar point cloud or airborne laser pulse return frequency distribution were used as an indicator for the presence of leaf area, then the amount of modelled light transmitted to the base of the canopy could be systematically overestimated in the airborne case and underestimated in the terrestrial case. This highlights the need for the calibration of both airborne and terrestrial lidar datasets if used for such radiation modelling purposes.

Height of maximum crown diameter obtained from terrestrial lidar

The height of the maximum crown diameter for individual trees will impact the height at which canopy closure will occur, and therefore may influence how laser pulse returns are distributed within the canopy. For example, intersecting branches (e.g., no gaps) between two trees may (*i*) provide enough biomass for a laser pulse return to be recorded by the receiver optics, thereby disallowing any further returns within two or more metres of the initial return; and (*ii*) block further penetration of laser pulses into the canopy. Unfortunately, the

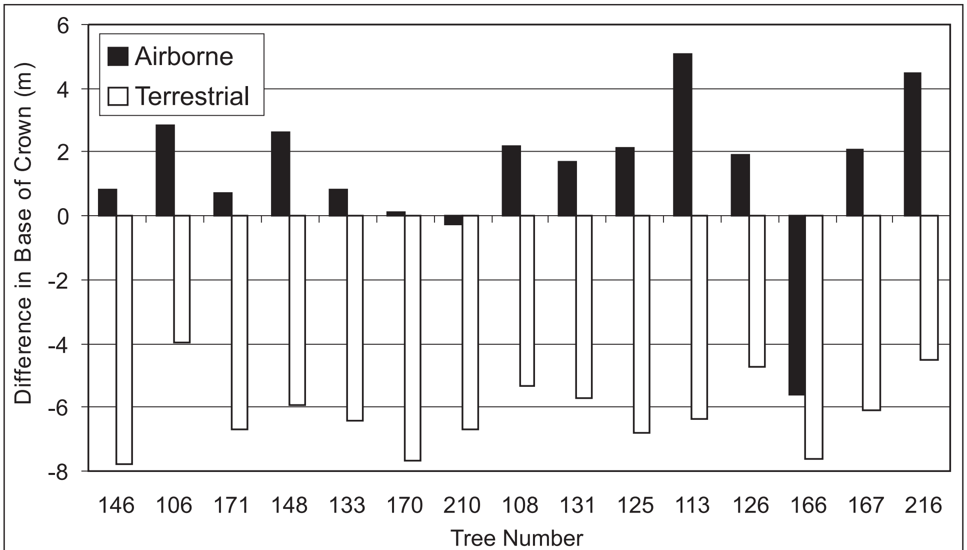

Figure 3. Differences in individual tree base-of-live-crown estimates for airborne and terrestrial lidar in comparison with field measurements (field height – lidar height). In most cases, the depth of maximum canopy penetration for airborne laser pulse returns is higher in the canopy. Laser pulses emitted from terrestrial lidar are lower due to sampling dead branches below the base-of-live-crown.

height at which the maximum crown diameter occurs can be difficult to estimate in the field. However, this can be visibly identified within the point clouds collected using terrestrial lidar. Examination of the height of maximum crown diameter from terrestrial lidar will help to explain structural influences on the distribution of airborne laser pulse returns within individual tree crowns, as described in **Figure 4**.

In this study, it was found that maximum crown diameters estimated from terrestrial lidar data occurred at heights of between 15.3 and 20.4 m agl. It is expected that as the height of the maximum crown diameter decreases (e.g., is lower to the ground), greater proportions of laser pulses will be returned from deeper within the canopy because the exposed tree crown surface area available for laser pulse return will increase with depth (Magnussen and Boudewyn, 1998). This hypothesis was tested, but no clear relationships were observed, except for a weak positive correlation (R^2 = 0.07) between the lowest within-canopy return from airborne lidar and the height of maximum crown width. For all but one tree, however, the greatest proportion of airborne laser pulse returns was above the height of maximum crown diameter (ranging from heights of 17.5 to 21.5 m agl and averaging 3 m above maximum crown diameter). Also, at heights below the maximum crown diameter, the frequency of laser pulse returns diminished significantly. These results are illustrated using percent frequency distributions of airborne and terrestrial laser pulse returns within the crown for three typical trees (**Figure 5**).

Height of median canopy laser pulse return obtained from airborne lidar

It was proposed by Magnussen and Boudewyn (1998) that the median height of canopy laser pulse returns within a plot of trees may be influenced by, and therefore an indicator of, mean LAI. Also, the depth of laser pulse penetration may be related to gaps within the canopy and LAI (Lovell et al., 2003; Lee et al., 2004) or variations in laser scanner settings (Naesset, 2005). From the 15 trees in this study, the average median canopy laser pulse return height was 20.4 m (sd = 1.0 m) and varied with canopy openness and crown proximity. This median height occurs approximately 1 m lower within the canopy than the maximum frequencies for 11 (73%) of the 15 trees. Therefore, if greater numbers of pulses return from foliage near the top of the canopy, the median pulse return height will be preferentially distributed (relative to the foliage profile) higher in the canopy, suggesting that in this closed-canopy conifer plantation it would be unlikely for median laser

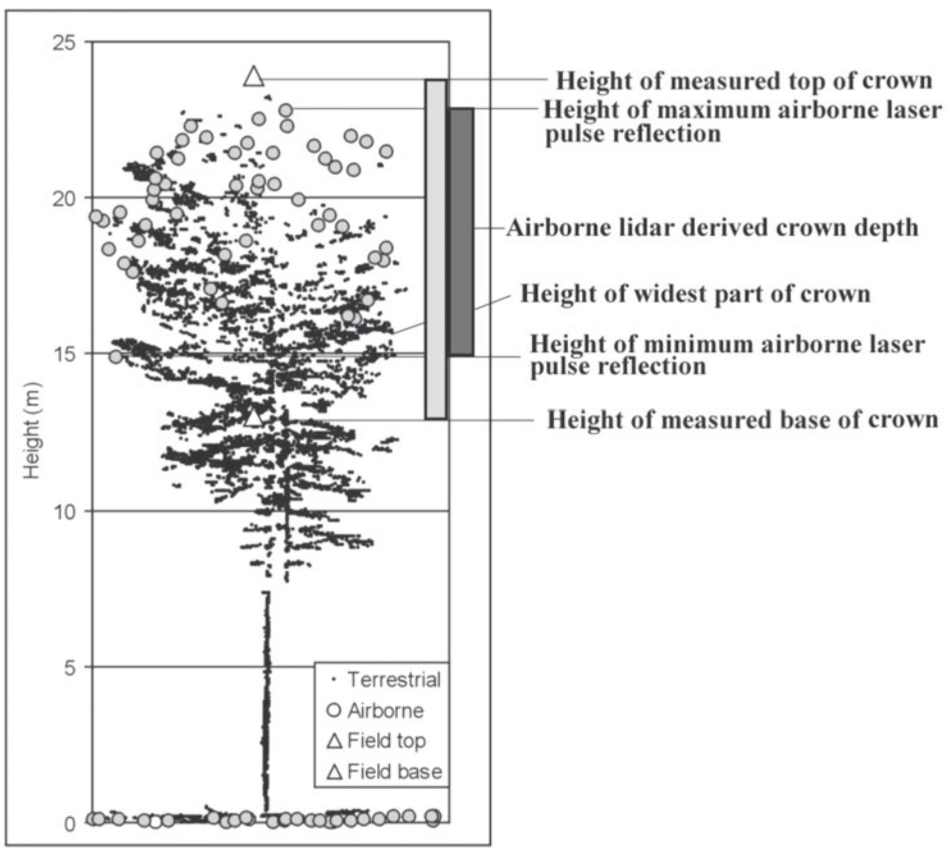

Figure 4. Airborne and terrestrial lidar point cloud data for a sample tree, illustrating differences between maximum and minimum laser pulse returns within the crown (in comparison with measured top-of-live-crown and base-of-live-crown). Depth-of-crown between maximum and minimum laser pulse returns is significantly underestimated compared with field measurements.

pulse return height to be solely an indicator of LAI. It was also found that the median laser pulse return height occurred, on average, 2.6 m higher in the canopy than the height of greatest crown diameter (differences ranged from –0.2 m to 6.6 m). Therefore, for closed canopies, the height of the median laser pulse may not coincide with the part of the canopy that contains the greatest leaf area on a per tree basis, if standard techniques are used (e.g., square metres of spherical needles per square metre of ground surface).

Concluding remarks

This study has addressed a variety of questions related to the distribution of laser pulses within a closed-canopy red pine plantation using a combination of coincident field measurements, terrestrial lidar data, and airborne lidar data. Terrestrial lidar data greatly compliment standard forest mensuration techniques and are a useful source of forest canopy structural information that enables a better understanding of airborne lidar pulse return distribution patterns within forest canopies.

The following main observations were made:

(1) Airborne and terrestrial lidar data used in this study underestimated field-measured tree heights by approximately 1.1 and 1.2 m, respectively. If these technologies were used to directly quantify individual tree heights without correction, then any use of standard allometric yield or biomass equations will lead to systematic underestimations of these quantities.

(2) Airborne lidar data tended to overestimate the base-of-live-crown height by 1.4 m, on average. This has implications for direct sampling and estimation of crown depth, leaf area, and biomass from airborne laser systems. Improved understanding of the distribution of laser pulse returns within canopies and optimization of airborne laser surveys for maximum foliage representation is still needed. Terrestrial lidar pulse returns tended to underestimate the base-of-live-crown by 6.2 m, on average, because of laser pulse returns from dead branches.

(3) The average field-measured height of the base-of-live-crown was 14.6 m (for all trees), and the average height of the lowest within-canopy airborne laser pulse return was 16.0 m. The average height of maximum crown diameter (or maximum canopy closure) obtained from terrestrial lidar occurred at approximately 18.0 m. Therefore, airborne laser pulse returns occurred below the height at which the canopy is mostly “closed”, i.e., these returns were most likely triggered within the foliage rather than from the outer envelope of tree crowns. However, the average median height of airborne laser pulse returns was 20.4 m, and average maximum laser pulse return height was only slightly above this at 20.8 m, illustrating that the majority of airborne laser pulse returns are distributed high in the canopy and tend to cluster near the upper outer envelope of the closed-canopy tree crowns. These observations suggest that in closed-canopy conifer plantations airborne lidar should be suitable for providing upper canopy and tree crown

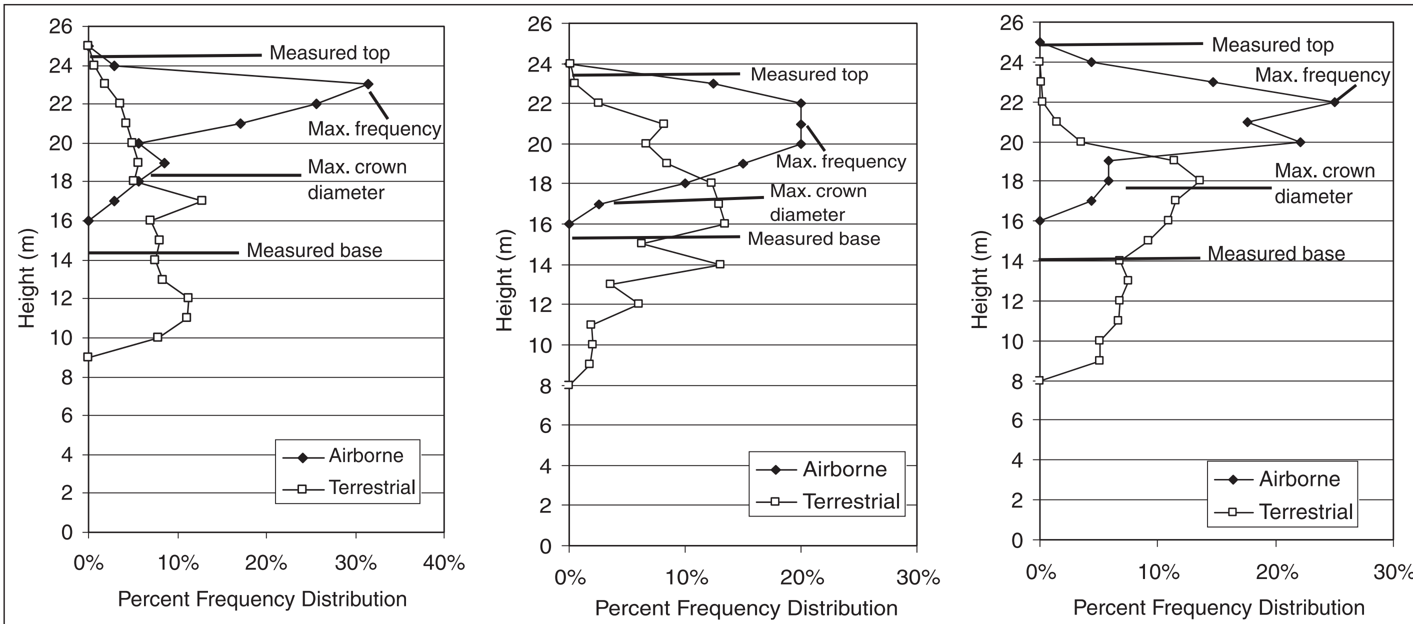

Figure 5. Percent frequency distributions of within-crown airborne and terrestrial lidar pulse returns for three typical trees. For airborne lidar, the maximum frequency of laser pulse returns tends to occur higher in the crown than the maximum crown diameter. Frequency distributions from the terrestrial lidar data illustrate significantly fewer top-of-live-crown returns than returns from the base of the crown. Higher sampling frequencies obtained by terrestrial lidar at the base of the crown are related to dieback below the base-of-live-crown and the horizontal scanning geometry of the sensor. Our field sampling methodology did not account for dead branches below the live crown.

morphological information, although it does not necessarily provide much structural data on the full foliage profile.

Significant differences have been found in this study between lidar estimates and field measurements of canopy height metrics. Further analysis is required to (*i*) optimize sensor and survey configuration settings, and (*ii*) calibrate the relationships between laser pulse return sample distributions and properties of the canopy structure. For example, a more thorough sampling of the lower parts of canopies is possible with modern airborne multiple pulse return systems or full waveform return digitizers. This increased sampling ability does not necessarily mean, however, that there will be a more accurate re-creation of the full foliage distribution. It is therefore important that future research concentrates on improving our understanding of how laser pulse returns are actually "triggered" within canopy environments and how this trigger event might be influenced by changing canopy properties or data acquisition parameters such as sensor settings or survey configuration.

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