

Errors in LiDAR ground elevation and wetland vegetation height estimates

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Abstract: An airborne scanning LiDAR (light detection and ranging) survey using a small footprint discrete pulse return Airborne Laser Terrain Mapper (ALTM) was conducted over the Utikuma Boreal wetland area of northern Alberta in August 2002. These data were analysed to quantify systematic LiDAR errors in: a) ground surface elevation; and b) vegetation canopy surface height. Of the vegetation classes, aquatic vegetation was associated with the largest error in LiDAR ground surface definition (+0.15 m, $\sigma = 0.22$), likely a result of saturated ground conditions. The largest absolute errors in LiDAR canopy surface height were associated with tall vegetation classes. However, the largest relative errors were associated with low shrub (63%) and aquatic vegetation (54%) classes. The openness and orientation of vegetation foliage was thought to enhance laser pulse canopy surface penetration in these two classes. Raster canopy height models (CHMs) systematically underestimated field validation heights by between 3% (aspens and black spruce) and 64% (aquatic vegetation). It is recommended that robust LiDAR canopy surface height correction methods be investigated that are universally applicable to vegetation classes of all species and heights.

1. INTRODUCTION

To explore the effects of natural and anthropogenic stresses on the hydro-ecology of the Western Boreal Plain region, a collaborative research project was initiated entitled "Hydrology, Ecology, And Disturbance (HEAD) of the western boreal wetlands" (Devito, et al., 2000). The focal point of the HEAD study is a hydro-geologic gradient located on the Utikuma Uplands, north of Utikuma Lake in Alberta, Canada. An airborne LiDAR data collection campaign was organised to produce a high-resolution ground digital elevation model (DEM_{ground}), a canopy digital elevation model (DEM_{canopy}) and canopy height model (CHM) to be used in process-based energy balance and hydrological models within the region.

Models used to calculate landcover energy fluxes have been shown to be sensitive to errors in vegetation parameterizations and the need for accurate height estimates has been highlighted (Crawford and Bluestein, 2000; Schaudt and Dickinson, 2000). Roughness length calculations derived from profiling LiDAR estimates of vegetation height have been shown to agree well with field measurements over grass and shrubland areas (Menenti and Ritchie, 1994). In a similar study conducted by Weltz et al. (1994) there was some underestimation of canopy height, a result common to many scanning LiDAR studies (e.g. Magnussen et al., 1999; Gaveau and Hill, 2003). Underestimating canopy height is typically attributed to: (i) laser pulse penetration into the foliage; (ii) insufficient representation of canopy apices due to low sample point density (St-Onge et al., 2003) or (iii) ground height overestimation due to minimal pulse penetration through dense vegetation (e.g. Weltz et al., 1994; Reutebuch et al., 2003). Ground height biases up to 0.2 m have been observed for wetland and riparian vegetation covers (Bowen and Waltermire, 2002; Töyra et al., 2003) and these biases have been found to vary with landcover (Töyra et al., 2003; Hodgson and Bresnahan, 2004).

Many studies have investigated the use of LiDAR for tree height measurement and found good relationships between LiDAR and field measures with r^2 values typically ranging from 0.85 to 0.95 (Maclean and Krabill, 1986; Ritchie, 1995; Naesset, 1997; Magnussen and Boudewyn, 1998; Means et al., 2000; Witte et al., 2001; Naesset, 2002; Naesset and Okland, 2002; Popescu et al., 2002; Lim et al., 2003a; Lim et al., 2003b). According to Davenport et al. (2000) and Cobby et al. (2001) short vegetation heights can be predicted from the standard deviation of LiDAR heights. However, these studies did not ascertain the level of

error associated with directly measuring the canopy surface height for short (< 2 m) vegetation. In addition, the approach used filters the data with a moving window to model vegetation heights and thus will tend to generate data of a lower resolution than the raw LiDAR data.

The objective of this paper is to evaluate the capability of airborne scanning LiDAR to directly measure vegetation canopy height for a range of common vegetation types within the WBP environment. The accuracy and systematic biases within the derived ground elevation and vegetation height data will be quantified. The analysis presented is one of the first in-depth assessments of vegetation class dependant error in LiDAR estimates of both ground height and vegetation canopy height

The study was conducted in the Utikuma Uplands located north of Utikuma Lake, Alberta, Canada along a 40 km \times 6 km transect. Topography along the hydrogeologic gradient is subtle with a total relief of about 75 m. Vegetation is dictated by soil moisture conditions with relatively dry sites dominated by trembling aspen (*Populus tremuloides* Michx.), very dry sites dominated by jack pine (*Pinus banksiana* Lamb.), and imperfectly drained peatland sites dominated by black spruce (*Picea mariana* Mill.).

2. DATA COLLECTION

The LiDAR survey was conducted in August 2002 using an Optech Inc. ALTM model 2050. The ALTM 2050 is a high-resolution discrete dual pulse return (first and last) small footprint scanning LiDAR with manufacturer quoted vertical and horizontal standard deviation accuracies of ± 0.15 m and 1/2000 flying height, respectively.

The entire area was surveyed at relatively narrow scan angle swaths ($\pm 16^\circ$) with appropriate distance between flight lines to facilitate 50% sidelap (or 200% total aerial coverage). Twenty flight lines were surveyed in total. This configuration increased the chance of obtaining returns from the true ground level over as much of the polygon as possible. The emitted LiDAR sample point density, was greater than 3 per m^2 . All LiDAR and ground truth data were georegistered to UTM coordinates using two global positioning system (GPS) base stations located within the area that was surveyed.

Several differential kinematic GPS surveys were conducted coincident with the airborne survey to locate reference points

(RPs) for comparison with the LiDAR data. These surveys were conducted to establish RPs on ground surfaces that were: i) non-vegetated highway surfaces, to assess the vertical accuracy of the raw LiDAR data; ii) covered by a short (< 5 m tall) vegetated canopy, to compare with LiDAR data that had penetrated through the vegetation and had been classified as ground returns. These data were collected to quantitatively assess whether the LiDAR data were within expected tolerances; i.e. ± 0.15 m (1 standard deviation) for elevation data over well-defined surfaces. For less well-defined vegetation covered surfaces, the only known comparable statistics detailing vertical bias in ground elevation for a northern wetland environment range from + 0.07 m (± 0.15 m) to + 0.15 m (± 0.26 m) for graminoid and willow scrub, respectively (Töyra et al., 2003). Analysis carried out by Hodgson and Bresnahan (2004) in South Carolina demonstrated both positive and negative absolute errors, from -0.06 m (± 0.23 m) to + 0.06 m (± 0.19 m), in LiDAR ground elevation for various ground covers.

Non-vegetated RPs were surveyed along road centre and shoulder markings at 100 m intervals along a highway running across the survey polygon. (RMS errors in the GPS RP locations were in the mm to cm range.) RPs lying beneath vegetation cover were collected along six relatively flat transects of 30 m to 60 m in length across heterogeneous ground cover types. Each transect was marked with stakes and a 30 m tape, and RPs were collected equal intervals (from 0.5 m to 2 m depending on local vegetation height variability). Ground cover types varied along the transects and were divided into four short vegetation classes (Figure 1) based on the Ducks Unlimited vegetation classification of the Utikuma wetland complex (Ducks Unlimited Canada, 2002): a) Aquatic vegetation – AQ; b) Grass and herbs – GH; c) Low shrubs – LS (< 2 m); d) Tall shrubs – TS (2 m – 5 m).

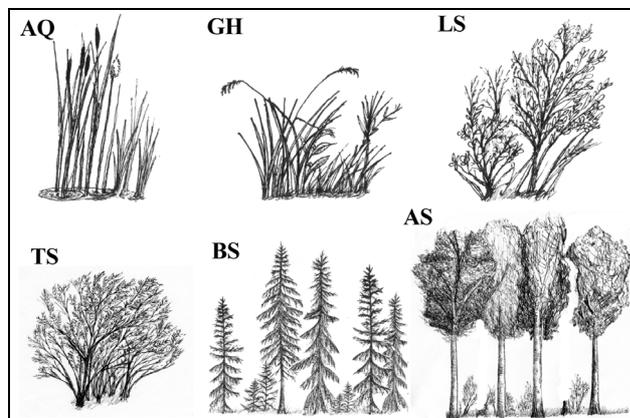


Figure 1. Vegetation classes sampled. Individual diagrams at different scales.

At each transect RP, the mean maximum vegetation canopy height within a 0.5 m radius around that point was visually estimated with a measuring staff (measurement uncertainty of up to ± 0.05 m) and noted along with a description of the vegetation type. RP and vegetation height data were collected simultaneously to ensure coregistration of the data. Collecting canopy height and GPS data was challenging under tall canopies and so only short vegetation classes could be investigated along transects. For tree vegetation classes, forest mensuration data were collected for a series of sample plots to characterize canopy height for subsequent comparison to plot-level LiDAR data. Two predominant endmember forest species belonging to the Ducks Unlimited classifications of “needle leaf conifer” and “deciduous” were chosen for this analysis (Figure 1): a) Needle leaf conifers (black spruce [*Picea mariana* Mill.]) – BS; and b) Deciduous (aspens [*Populus tremuloides* Michx.]) – AS.

Eight 15 m x 15 m plots were located using distance and bearing measurements to nearby RPs. Four plots each of aspen and black spruce were set up to represent deciduous and conifer endmember species, respectively. Homogeneous forest plots representing a range of height classes were sampled. Tree height and live crown length was measured using a vertex sonic hypsometer, diameter at breast height (DBH) with a standard DBH tape measure, and crown diameter was measured along north-south and east-west crown axes using a survey tape measure. In the aspen plots, all trees with a DBH greater than 9 cm were recorded. For the black spruce plots, all stems above 2 m in height were recorded, as trees with a small DBH could comprise significant canopy elements for this conifer species.

3. ANALYSIS

LiDAR data were processed by Optech Inc. and provided in UTM co-ordinates for all first and last laser pulse returns. Over hard impenetrable surfaces the first and last laser pulse returns for every emitted pulse are coincident. Over areas of tall canopy, the first laser returns are preferentially distributed throughout the upper canopy with the last returns nearer the ground. The laser pulse time interval meters within the ALTM hardware used in this study were unable to distinguish between first and last returns less than 4.6 m apart. Therefore, only single (i.e., coincident first and last) returns can be recorded in canopies lower than this height. The raw LiDAR data were classified into ground and vegetation returns using an automated algorithm in proprietary software by Optech Inc.

To assess the accuracy of the raw LiDAR elevation data, highway RPs were compared with LiDAR returns that were within a 0.5 m horizontal radius of a RP (error = LiDAR height – RP height). The road was flat and all RPs were collected at least 1 m from the road edge. The highway traversed the entire width of the study area and the RPs collected were compared with raw LiDAR data sampled from every flight line. Vegetated transect RPs were also compared to ground classified LiDAR returns for the short vegetation classes to evaluate the influence of vegetation on LiDAR ground height accuracy. In areas of steep slope, positional error in the LiDAR data will introduce a vertical error component (Hodgson and Bresnahan, 2004). To minimise vertical errors due to positional uncertainty, highway and transect RPs were collected over flat areas.

Ground classified LiDAR sample point densities are typically irregularly spaced over the ground surface due to varying degrees of vegetation density. To determine LiDAR heights above ground level and to generate canopy height models (CHMs), the ground and vegetation data can be interpolated to a common raster array (e.g. Lim et al., 2003a). These two surfaces are referred to as DEM_{ground} and DEM_{canopy} for the bare-ground and vegetation canopy surfaces respectively. In this study, both the ground surface and vegetation canopy height data were rasterised to a 1 m grid so that field measured RPs and vegetation heights could be compared with their interpolated LiDAR equivalents.

All ground-classified data were rasterised to generate a 1 m resolution digital elevation model (DEM_{ground}). An inverse distance weighted routine was chosen as it maintains point integrity, enables interpolation using a simple distance weighted function and is relatively fast (Golden Software Inc., 2002). A search radius of 10 m was chosen so that a surface would be interpolated in areas of sparse LiDAR data coverage. The highway and ground transect GPS control points were compared to the LiDAR DEM_{ground} to estimate absolute errors resulting from the interpolation.

The DEM_{canopy} for the survey polygon was rasterised from the vegetation classified LiDAR data. To reduce the possibility of biasing the interpolated DEM_{canopy} model downwards, the LiDAR data were filtered so that only the highest points within each 0.5 m x 0.5 m window were used for rasterisation. As with the ground DEM, an inverse distance weighted rasterisation procedure was adopted but the search radius was reduced to 1 m so that a vegetation canopy would not be interpolated in areas of no data. A raster CHM was then created by subtracting DEM_{ground} from DEM_{canopy}.

The LiDAR point-based estimates of canopy surface height for short vegetation were derived by extracting the highest laser pulse return from within a 0.5 m radius of every transect RP and subtracting the RP elevation. The canopy lidar return was compared with the RP height rather than another LiDAR return at ground level, as the purpose of this analysis was to assess the level of vertical correspondence between the uppermost canopy LiDAR returns and the actual surface of the vegetation canopy. The raster-based estimates of canopy height were extracted from the CHM for each transect control point using the value of the 1 m x 1 m grid cell closest to each RP. The LiDAR point-based and raster-based estimates of canopy surface height were then compared to the field measured heights. Summary statistics and regressions were performed for each short vegetation class to assess the error in LiDAR point-based and raster-based estimates due to laser pulse foliage penetration, and to assess whether or not there was significant correlation with field measurements. Some height error is to be expected due to the inherent horizontal uncertainty (up to ~ 0.6 m) in the LiDAR XY coordinate. Height errors due to LiDAR point position will be maximised in areas of variable canopy surface height.

In order to make a direct comparison of LiDAR point- and raster-based height estimates with the forest plot mensuration data, a half ellipsoid tree crown model was employed to describe the vertical distribution of canopy surface exposure within each plot. The model used was similar to those described by Pollock (1996) and Nelson (1997), and has been used in other LiDAR canopy simulation studies (Holmgren et al., 2003). Tree height, crown length and crown radius were the parameters necessary to model the plot-level canopy surface distribution. Although black spruce and aspens tend to have quite different shapes (Figure 1), the same half ellipsoid function was applied to both as it was assumed that the major differences in crown shape would be accommodated by the measured differences in crown lengths and diameters. Other studies have also used the same function to describe a variety of tree types (e.g. Straub et al., 2001). By adopting an ellipsoidal model, as opposed to a spherical or conical, potentially large errors are mitigated (Nelson, 1997).

A vertical frequency distribution of exposed canopy surface area was generated for each plot and the average canopy height for each plot was calculated. Vertical area frequency distributions were also generated for both the first pulse return LiDAR and raster data for comparison (only first returns were considered, as these were assumed to most likely represent canopy surface). The LiDAR distribution was generated by first dividing the area of each plot into the total number of all laser pulses reflected from the plot to calculate the area represented by each pulse A_r . The LiDAR data were then detrended to remove the influence of topography by subtracting the interpolated raster ground elevations associated with each LiDAR return, and a vertical frequency distribution of the number of returns multiplied by A_r was plotted at 1 m height quantile intervals. The raster CHM distribution was generated by plotting the vertical frequency of grid cells in each height quantile (A_r for each grid cell = 1 m²). Average canopy surface heights were considered to be the mean quantile height of the area frequency distributions. The volumes

beneath the plot canopies using each method were calculated using equation 1.

$$V = \sum_{q=0}^{q=\max} (H_q \times F_q \times A_r) \quad (1)$$

Volume V was calculated by multiplying the quantile heights H_q by their respective frequencies F_q and the area represented by each pulse, then summing the results.

4. RESULTS AND DISCUSSION

The average dropout rate (lost laser pulses as a percentage of the total emitted pulses) recorded by the ALTM during the survey was approximately 8%, with a maximum loss of 19% over scan lines with a high proportion of open water. The average point density for the entire polygon was between 2 and 5 points per m², depending on swath overlap, local dropout rate and division of first and last pulse returns. Following the automated vegetation classification, 24% of all the raw LiDAR data were classified as ground points. The point density of ground-classified returns over the survey polygon was between 0.5 and 1.3 returns per m². However, the ground class point density was highly variable, with higher densities over open dry ground and lower densities over areas of dense canopy and wet ground.

After subtracting highway RP elevations from LiDAR returns within a 0.5 m horizontal radius, the mean height difference was found to be 0.00 m with a standard deviation of 0.07 m. These results are consistent with those of Töyrä et al. (2003). The raster DEM comparison showed similar results (Table 1). These results demonstrate that the ALTM 2050 was accurately calibrated and performing well within specification.

| | | Landcover Hwy | Ground data | Aquatic | Grass herbs | Low shrubs | Tall shrubs |
|---------------------------------|----------|---------------|-------------|---------|-------------|------------|-------------|
| Raw LiDAR height error stats | Mean | 0.00 | +0.07 | +0.15 | +0.02 | +0.06 | +0.06 |
| | Min | -0.18 | -0.15 | -0.15 | -0.13 | -0.09 | +0.02 |
| | Max | +0.25 | +0.91 | +0.91 | +0.49 | +0.49 | +0.08 |
| | St. Dev. | 0.07 | 0.16 | 0.22 | 0.10 | 0.12 | 0.03 |
| Raster LiDAR height error stats | N | 95 | 127 | 35 | 45 | 43 | 4 |
| | P | ND | < 0.01 | < 0.01 | ND | < 0.01 | < 0.01 |
| | Mean | 0.00 | +0.04 | +0.12 | 0.00 | +0.01 | +0.11 |
| Raster LiDAR height error stats | Min | -0.19 | -0.30 | -0.10 | -0.25 | -0.30 | -0.16 |
| | Max | +0.13 | +0.88 | +0.88 | +0.39 | +0.31 | +0.36 |
| | St. Dev. | 0.08 | 0.14 | 0.18 | 0.10 | 0.13 | 0.16 |
| | N | 95 | 208 | 45 | 77 | 72 | 14 |
| Raster LiDAR height error stats | P | ND | < 0.01 | < 0.01 | ND | ND | < 0.01 |

Table 1. Ground classified LiDAR and raster ground DEM height errors relative to GPS reference points for each landcover. P = tail probability of no difference in height; ND = no significant height difference.

The average difference between ground classified LiDAR returns and RPs collected from vegetated surfaces was +0.07 m (± 0.16 m). Similar results were returned for the raster DEM and ground control point comparison with a mean offset of +0.04 m (± 0.14 m) (Table 1). LiDAR pulses lying above RPs were also observed in vegetated areas by Töyrä et al. (2003) and can be explained by the reduced probability of LiDAR pulse penetration to true ground level. Some error in lidar ground return elevation is usually attributable to misclassification of lidar returns by the classification algorithm used (Raber et al. 2002). However, for this study, the classification algorithm was kept spatially constant and any variation in the magnitude of vertical error can be attributed to localised ground cover conditions. It is apparent that the vertical offset varied with vegetation type, with negligible offsets of +0.02 m (raw LiDAR) and 0.00 m (raster DEM) for the grass/herb class and relatively

large offsets of +0.15 m (LiDAR) and +0.12 m (raster) for the aquatic vegetation class (Table 1).

Foliage orientation, height, density and ground surface type can all potentially influence the likelihood of laser pulses reaching and reflecting from the true ground level. The larger offset for aquatic vegetation is probably not a simple function of vegetation height, as both low shrub and tall shrub ground covers display taller vegetation heights (Table 2). Along the transects visited, aquatic vegetation was not noticeably denser than other vegetation types. Aquatic vegetation tended to have the most uniform structure with most stems pointing upwards and a small planimetric surface area relative to other vegetation classes (Figure 1). With such a foliage arrangement, laser pulse penetration is somewhat dependent on incident scan angle (Davenport et al., 2001). However, for this study, the average scan angle incident on the ground was close to nadir at 8°, and should therefore ensure a high rate of laser pulse penetration through the canopy. It is speculated that the relatively large average difference of 0.15 m between LiDAR and RP height is related to the ground surface condition. The ground cover beneath most of the aquatic vegetation sampled tended to be open water or saturated organic soils. These types of ground cover reflect weakly in the 1067 nm infrared wavelength of the laser and thus the likelihood of a ground return is reduced relative to drier and more reflective surfaces. In the absence of strong laser backscatter from the true ground surface, laser returns will therefore tend to be biased upwards into the more highly reflective foliage.

| Statistic | Vegetation class | Aquatic | Grass and herbs | Low shrubs < 2 m | Tall shrubs 2 – 5 m |
|------------------------------------|------------------|-----------------------|-----------------|------------------|---------------------|
| | | Field height measures | Average | 0.45 | 0.30 |
| | Minimum | 0.01 | 0.05 | 0.10 | 2.30 |
| | Maximum | 1.00 | 0.80 | 2.00 | 5.00 |
| | Std dev. | 0.25 | 0.20 | 0.59 | 0.94 |
| | Number (total) | 27 (49) | 31 (77) | 44 (71) | 12 (16) |
| Pont-based LiDAR height statistics | Average | 0.21 | 0.20 | 0.30 | 2.92 |
| | Minimum | -0.04 | -0.02 | -0.07 | 0.10 |
| | Maximum | 0.52 | 0.83 | 1.48 | 5.03 |
| | Std dev. | 0.14 | 0.20 | 0.31 | 1.46 |
| | Number (total) | 27 (40) | 31 (57) | 44 (55) | 12 (12) |
| Mean difference | | -0.24 (53%) | -0.10 (33%) | -0.52 (63%) | -0.84 (22%) |
| P | | < 0.01 | < 0.05 | < 0.01 | < 0.10 |
| Raster CHM statistics | Average | 0.16 | 0.26 | 0.43 | 2.67 |
| | Minimum | 0.03 | -0.04 | -0.01 | 1.19 |
| | Maximum | 0.55 | 0.91 | 1.76 | 4.70 |
| | Std deviation | 0.12 | 0.26 | 0.38 | 1.30 |
| | Number (total) | 27 (32) | 31 (44) | 44 (55) | 12 (16) |
| Mean difference | | -0.29 (64%) | -0.04 (13%) | -0.39 (48%) | -1.09 (29%) |
| P | | < 0.01 | > 0.1 | < 0.01 | < 0.05 |

Table 2. Field, LiDAR and raster CHM vegetation height error statistics for short (< 5 m) vegetation classes. Number = comparative sample used for generation of statistics; (total) = total number of data collected; Mean difference = LiDAR canopy height – field canopy height; P = tail probability of no difference to field measured heights.

Comparative statistics of the six transects of field vegetation height measurements, filtered LiDAR heights above RPs and raster CHM heights are presented by vegetation class in Table 2. Table 2 demonstrates that there is a tendency for the filtered point-based LiDAR returns (i.e. highest returns within a 0.5 m window around the RP) to penetrate the vegetation canopy surface but the amount of penetration is highly variable along the transects. (It should be noted that although positional error in the LiDAR data will lead to some random vertical error in canopy height estimation, the consistent underestimation of height from the LiDAR derived methods (Table 2) indicates that positional uncertainty in the LiDAR returns is not the source of

vertical bias.) This is likely a function of ground height interpolation errors and the larger 1 m search radius used for raster interpolation compared to the 0.5 m search radius used to find the highest laser pulse relative to a GPS reference point.

From Table 2 it is apparent that the amount of foliage penetration varied with vegetation type. Average foliage penetration ranged from 0.10 m (33%, $P < 0.05$) for the grass and herb class to 0.84 m (22%, $P < 0.10$) in the tall shrub class. However, low shrubs displayed the highest proportion of vegetation surface underestimation with average laser pulse penetration of 63% (0.52 m, $P < 0.01$) into the vertical foliage profile. The relatively open structure of low shrubs (i.e. space between stems) compared to other classes (Figure 1) likely allows greater penetration of a laser pulse into the foliage before sufficient energy is backscattered to register a signal within the electro-optical sensors of the ALTM. Aquatic vegetation also demonstrates a high proportion of foliage laser pulse penetration (53%, $P < 0.01$) and this is likely due to its generally vertical foliage orientation projecting a minimal planimetric surface area exposure (Figure 1). The average aquatic vegetation raster CHM estimate displays the greatest difference from field measurements (64%, $P < 0.01$), and this is likely a function of both: a) increased laser penetration into foliage; and b) overestimation of true ground surface height beneath this kind of vegetation (Table 1).

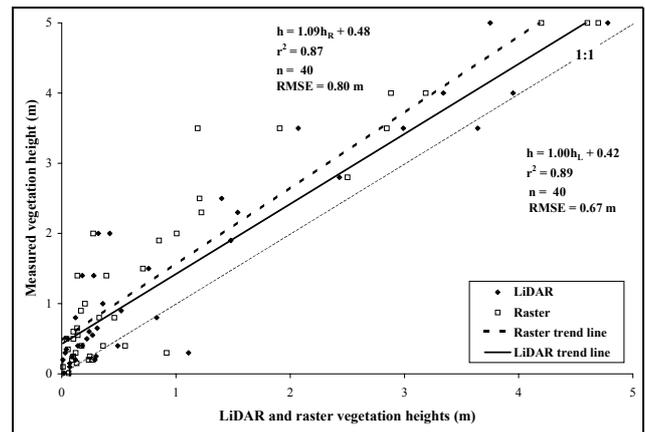


Figure 2. Plot of short vegetation height data / LiDAR and raster height data per transect and vegetation class. h = vegetation height; L = point-based LiDAR; R = raster CHM. (Data thinned below 1 m measured vegetation height to remove heteroscedacity.)

The relationships between measured vegetation canopy heights and the corresponding LiDAR derived estimates for transect measurements are illustrated in Figure 2 (data points below 2 m measured vegetation height have been resampled by keeping every third point and deleting the rest to create a more uniform distribution for regression analysis). After performing linear regression on each individual vegetation class, it was found that a statistically significant relationship existed between the point-based LiDAR and field vegetation height measures for all classes. The relationship between field and raster CHM measures are, in all cases, weaker and for aquatic and low shrub classes, the relationship is not significant at the 99% confidence level. All coefficient of determination values returned for regression lines passing through the origin (0 m vegetation height) for all but the tall shrub vegetation classes, were null and indicate that the true vegetation heights cannot be predicted using a simple multiplication factor of the LiDAR or raster CHM estimates.

Figure 3 suggests that laser pulses either penetrate slightly into the foliage, or the tops of the tallest trees are not adequately sampled. This general finding is in agreement with findings from

other studies (Magnussen et al., 1999, Gaveau and Hill, 2003). Although both forest endmember types display a similar underestimation of exposed vegetation area at the upper height quantiles, the two distributions differ markedly at lower height quantiles. For the aspen species with relatively well-defined canopy top and base, there appears reasonable correspondence between the mensuration data modeled, point-based LiDAR and raster CHM canopy surface area distributions in the lower canopy. Overall, the underestimation of upper canopy area combined with a reasonable estimate of lower canopy area leads to an approximately 10% underestimate in the total canopy volume for aspen trees (Figure 3). However, the canopy surface area at the mid to lower height quantiles (above undergrowth layer) in the black spruce plots is overestimated in the LiDAR and raster distributions. This leads to overestimates of black spruce canopy volume of 3% (point-based LiDAR) and 26% (raster CHM) despite underestimating the canopy surface area at the upper quantiles.

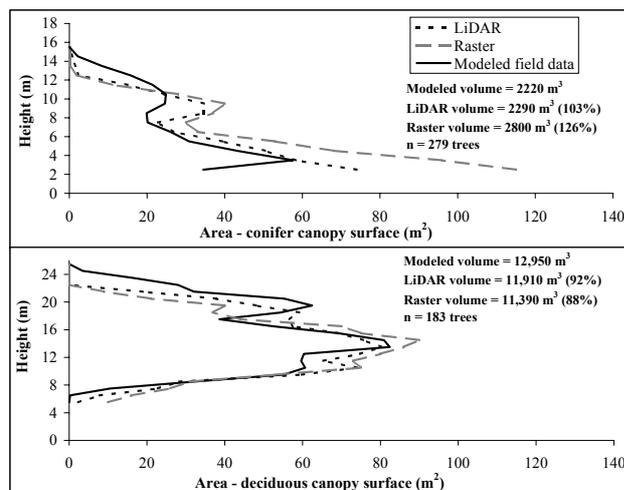


Figure 3. Combined canopy surface area distributions per height quantile for all plots within each forest vegetation class.

Given that significant foliage penetration was observed in the short vegetation classes (Table 2), and that Gaveau and Hill (2003) observed this phenomena directly for trees, it can be assumed that laser penetration into the canopy is partly responsible for the underestimation of exposed canopy surface area in the upper height quantiles (Figure 3). However, it should be noted that the two forest endmember classes differ markedly in canopy morphology, with relatively large crowns and closed canopy for the aspens and small crowns with open canopy for the black spruce. The smaller conifer tree crowns result in a reduced likelihood of a laser pulse sampling the upper quantiles of an individual tree, and therefore systematically bias the sample distribution downwards. This is evidenced in the canopy surface area distributions in Figure 3, where this bias has led to an apparent down shift in the overall black spruce distribution and an overestimation of area at lower quantiles. These data, therefore, demonstrate influences of both laser pulse foliage penetration and laser pulse sample density.

5. CONCLUSIONS

This study has provided an assessment of LiDAR based errors in ground elevation, vegetation height and a sensitivity analysis of hydrological friction parameter estimates for six dominant vegetation classes within a Boreal wetland environment. Comparing raw LiDAR data points with 95 highway reference points collected across the entire survey polygon revealed no vertical bias. The standard deviation in the LiDAR data over the RPs was ± 0.07 m. After subtracting field GPS elevations from

ground classified LiDAR data for 127 RPs over vegetated transects, an average bias of $+0.07 (\pm 0.16$ m) was found ($+0.04$ m in rasterised LiDAR data). The observation of ground height errors in vegetated areas is consistent with the findings of other studies (Töyrä et al. 2003; Hodgson and Bresnahan, 2004). The vertical bias was found to vary with vegetation cover, from no significant difference for grass and herbs to $+0.15$ m for aquatic vegetation. It is believed that LiDAR ground height estimation was most problematic for aquatic vegetation due to weak laser backscatter from the saturated ground conditions typically associated with this vegetation class. These observations support the rationale that ground level LiDAR point classification should be vegetation class dependent (e.g. Cobby et al., 2001).

After filtering the data for local maxima, the penetration of vegetation classified first pulse LiDAR returns into the canopy surface was found to vary with vegetation class and range from 0.10 m to 0.84 m. Maximum proportional foliage penetration was found to occur in low shrub vegetation ($> 60\%$) and this was thought due to the relatively open structure and low foliage density typical of this vegetation class. Aquatic vegetation was also susceptible to a high proportion ($> 50\%$) of laser pulse foliage penetration and this was thought related to the generally uniform and vertical orientation (minimal planimetric area projection) of aquatic vegetation in the study area. The tendency for both poor ground and canopy surface definition from LiDAR data in the aquatic vegetation class results in the greatest underestimations of height.

Actual forest canopy surfaces could not be compared directly with canopy laser pulse returns but after modeling canopy surface area distributions from forest mensuration data, a quantile-to-quantile comparison could be made with similar distributions generated from the frequency of all LiDAR returns and CHM grid cells. It was found that the average canopy surface heights derived from the LiDAR point-based area frequency distributions were good predictors of average plot-level tree height ($r^2 = 0.97$). Height and volume were both underestimated by 3% and 8%, respectively for the aspen plots, presumably influenced by laser pulse foliage penetration. For the black spruce plots, it was found that although LiDAR height was underestimated by 10%, the canopy surface volume was actually overestimated by 3% and 26% for the LiDAR point-based and raster CHM distributions, respectively. The increased volume estimate is a function of the LiDAR and raster CHM model of vertical canopy surface area distribution over-representing the intermediate and low foliage heights in the plots.

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