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Towards a universal lidar canopy height indicator

Chris Hopkinson, Laura Chasmer, Kevin Lim, Paul Treitz, and Irena Creed

Abstract. A light detection and ranging (lidar) canopy height study was conducted with 13 datasets collected using four different models of airborne laser terrain mapper (ALTM) sensors over 13 widely variable vegetation types ranging in average height from <1 m to 24 m at five sites across Canada between 2000 and 2005. The study demonstrates that the vertical standard deviation of all topographically detrended first and last laser pulse returns (L_{SD}) is a robust estimator of canopy height (Ht) for a wide variety of vegetation types and heights and lidar survey configurations. After regressing Ht against L_{SD} for 77 plots and transects, it was found that Ht could be predicted as a simple multiplication (M) of L_{SD} (M = 2.5, coefficient of determination (r^2) = 0.95, root mean square error (RMSE) = 1.8 m, tail probability (p) < 0.01). For forest plots only, L_{SD} was found to better predict average tree height (r^2 = 0.80, RMSE = 2.1 m, p < 0.01) than Lorey's height (r^2 = 0.59, RMSE = 3.0 m, p < 0.01). A test of the L_{SD} canopy height model was performed using stand heights (Ht_{FRI}) from an independent forest resource inventory (FRI) for four vegetation classes. Results from the raw FRI and modelled stand height comparison displayed close to a 1:1 relationship ($Ht_{FRI} = 0.97Ht_{LSD}$, r^2 = 0.73, RMSE = 4.7 m, p < 0.01, n = 38). All plot and transect canopy heights were also compared with the localized maxima of laser pulse returns (L_{max}). For individual surveys over homogeneous vegetation types, L_{max} generally provides a better canopy height indicator. Across all surveys and site types, however, L_{SD} was almost always shown to have a more consistent relationship with actual canopy height. The only observed exception was in the case of forest plot level Lorey's mean tree height. The advantages of using a multiplier of L_{SD} to estimate canopy height are its apparent insensitivity to survey configuration and its demonstrated applicability to a range of vegetation types and height classes.

Résumé. Une étude lidar (détection et télémétrie par ondes lumineuses) de la hauteur du couvert forestier a été menée à partir de treize ensembles de données collectés à cinq sites par tout le Canada durant la période 2000 à 2005. Quatre différents modèles de capteurs lasers aéroportés ont été employés pour effectuer la cartographie du terrain sur treize types de végétation éminemment disparates et dont la hauteur se situe entre moins d'un mètre jusqu' à 24 m. L'étude met en évidence que l'écart type vertical des première et dernière réflections de l'impulsion laser (L_{ET}) topographiquement décomposées est un estimateur robuste de la hauteur (Ht) du couvert sur une large gamme de types de végétation, de hauteurs différentes, et avec de différentes configurations lidar. La régression Ht par rapport à L_{ET} pour 77 plans cadastraux et virées transversales met en évidence qu'il est possible de prévoir Ht comme simple multiplicateur (M) du (M = 2,5, r^2 = 0,95, RMSE = 1,8 m, p < 0,01). Pour ce qui est exclusivement des plans cadastraux forestiers, il est apparu que L_{ET} prévoyait mieux la hauteur moyenne des arbres que ne le fait la hauteur moyenne des arbres de Lorey (r^2 = 0,59, RMSE = 3,0 m, p < 0,01). Un test du modèle L_{ET} pour déterminer la hautuer du couvert a été effectué à partir de mesures de la hauteur des peuplements enrégistrées dans un inventaire indépendant des ressources forestières (IRF) pour quatre catégories de végétation. La comparaison des résultats de l' IRF avec ceux qui avaient été modélisés fait preuve d'une relation avoisinant 1:1 (Ht_{FRI} = 0,97Ht_{LET}, r^2 = 0,73, RMSE = 4,7 m, p < 0,01, n = 38). Toutes les hauteurs des plans cadastraux et virées transversales ont été comparées aux maxima localisés des réflections de l'impulsion laser (L_{max}). Ce dernier (L_{max}) fournit généralement un meilleur indicateur de la hauteur du couvert forestier pour ce qui est des levés individuels de catégories de végétation homogènes. Toujours est-il que L_{ET} a fait preuve d'une relation plus cohérente à la hauteur réelle du couvert dans presque tous les cas pour tous les levés et tous les types de site. La seule exception notée était la hauteur moyenne des arbres de Lorey pour la forêt au niveau du plan cadastral. L'intérêt à utiliser un multiplicateur de L_{ET} réside dans les faits qu'il serait apparemment insensible à la configuration utilisée pour lever les données, et ses possibilités d'application à toute une gamme de types de végétation et catégories de hauteur.

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C. Hopkinson.[1] Applied Geomatics Research Group, Centre of Geographic Sciences, NSCC Annapolis Valley Campus, Middleton, NS B0S 1P0, Canada.

L. Chasner,[2] **K. Lim, and P. Treitz.** Department of Geography, Queen's University, Kingston, ON K7L 3N6, Canada.

I. Creed. Department of Geography and Department of Biology, University of Western Ontario, London, ON N6A 5C2, Canada.

[1]Corresponding author (e-mail: chris.hopkinson@nscc.ca).

[2]Present address: Applied Geomatics Research Group, Centre of Geographic Sciences, NSCC Annapolis Valley Campus, Middleton, NS B0S 1P0, Canada.

Introduction

Background

Airborne light detection and ranging (lidar) combines knowledge of the speed of light, the location and orientation of a laser pulse emitting and receiving instrument in space, and the time between laser pulse emission and the return of backscattered energy to survey the three-dimensional coordinates of objects at or near the earth's surface. Utilizing scanning technology, laser pulses can be redirected across the line of flight, resulting in a swath of laser pulse return (LPR) survey points beneath the aircraft. The resultant point data can be used to create high-resolution digital elevation models (DEMs) of the ground or digital surface models (DSMs) of vegetation canopy. Current technology can collect multiple laser pulse returns at pulse repetition frequencies (PRF) up to 100 kHz and can cover a ground swath greater than 3000 m, depending on flying altitude and scan angle. The resultant LPR positional accuracy is typically at the decimetre level. Most lidar sensors can be placed in one of two categories: (*i*) large-footprint (several metres) full waveform return or (*ii*) small-footprint (decimetres to metres) discrete elevation returns. For a more detailed introduction to lidar technology, see Baltsavias (1999) and Wehr and Lohr (1999).

Many studies using small-footprint discrete return airborne scanning lidar data have demonstrated strong empirical relationships between LPR metrics and vegetation height. Although much recent research is increasingly focusing on individual tree height estimation (e.g., St-Onge et al., 2000), most attention has been on comparing plot-level tree heights with some LPR-derived height metric. For example, Naesset (1997) found that for conifer stands ranging in height from 8 to 24 m, maximum LPR heights above the ground level correlated well with Lorey's mean tree height over a given area. Magnussen and Boudewyn (1998) expanded upon this work by investigating a canopy LPR quantile-based approach for estimating height for conifer plots ranging in height from 15 to 27 m. Similar LPR metrics were tested to estimate height and other biometric properties of tolerant hardwood plots of varying treatment and ranging in height from 10 to 30 m (Lim et al., 2003a). For a summary of research into tree height estimation from lidar data, the reader is referred to Lim et al. (2003b).

Common to the majority of lidar canopy height studies is (*i*) the tendency to focus on forest vegetation with canopy heights several metres above the ground; (*ii*) the derivation of LPR height metrics from canopy returns only, with ground-level returns typically used only for DEM generation; and (*iii*) the use of a single lidar sensor and survey configuration (e.g., flight altitude, scan angle, PRF, footprint size, and resolution). Consequently, many such studies have conceded that the derived LPR canopy height models are necessarily limited in their application.

There has been little effort thus far to identify an accurate yet potentially universal method of relating laser pulse return data to canopy height. Due to limited data availability, most lidar canopy height studies have favoured accuracy within a limited sample environment over universal applicability. This study presents a method that shows some promise in the search for a more universally applicable LPR canopy height model across a wide range of canopy height, canopy openness, vegetation type, and data collection configuration.

There is a large number of studies that have demonstrated high correlations between certain LPR metrics, such as maximum LPR height (L_{max}), and 90th or 95th percentile LPR distribution height within the canopy, and there are good reasons why these metrics should correspond with average canopy height. However, the challenge in identifying a universal LPR – canopy height relationship is that the shape of the LPR frequency distribution through the canopy can be influenced by (*i*) vegetation structural characteristics such as foliage density (e.g., Magnussen and Boudewyn, 1998), canopy height, and canopy openness; and (*ii*) lidar data acquisition factors such as pulse spacing, pulse size, pulse energy, and scan angle (e.g., Holmgren et al., 2003). The simplest and most robust approach yet adopted to infer canopy height is to isolate the localized maximum LPR elevation and subtract the associated ground elevation (e.g., Naesset, 1997). Incidentally, this is usually the approach implicitly adopted during the rasterization of lidar data to create DSMs for grid-based canopy height models (CHMs). The localized maxima approach is simple and robust but has some limitations in its application to estimates of average canopy height: (*i*) maximum canopy height is not necessarily related to average canopy height; (*ii*) the probability of L_{max} capturing the highest foliage within a sample area is influenced by pulse spacing and the shape of tree crown apices; and (*iii*) LPRs cannot be split into first and last returns in short vegetation canopy environments (Optech Incorporated, personal communication, 2005), and so only a single return is recorded from somewhere within the foliage.

Few studies have investigated the estimation of short (near ground surface) vegetation height from small-footprint discrete return scanning lidar. The work of Davenport et al. (2000) and Cobby et al. (2001) demonstrated that crop vegetation up to approximately 1.2 m in height could be predicted from the standard deviation of topographically detrended laser pulse returns (L_{SD}). Contrary to most studies focusing on forest canopy height estimation, the analysis presented in these two studies utilized all LPRs rather than just those identified as having returned from above the ground surface. An advantage of including all returns is that, if the overall proportion of ground returns is high, it is implied that canopy density (and therefore mean canopy surface height) is low and will act to pull the LPR distribution towards the ground and reduce the L_{SD}.

Rationale

The study presented here expands on previous research by investigating the relationship between L_{SD} and average canopy height across a range of sample sizes, vegetation functional groups, and canopy heights. For comparison, the analysis is also performed using the localized LPR maxima (L_{max}), as this is a robust and often-applied method of canopy height estimation.

It is common knowledge that for a normally distributed sample the range in the data can be approximated by a multiplier (M) of the standard deviation (σ) (at the 95% and 99% confidence interval levels, $M = 4\sigma$ and 6σ, respectively). The relationship between σ and total sample range varies with sample size and the shape of the distribution. In the case of vertical LPR distributions through vegetated plots of varying characteristics, however, we cannot expect sample size to remain fixed and, unlike normal sample populations, the range is limited by the vertical extent of the vegetation canopy. The knowledge, therefore, that each of the two tails of the LPR distribution represents ground level and upper canopy surface and that the confidence interval range within the tails of normal distributions can be estimated from sample standard deviation provides a reasonable basis for testing the relationship between L_{SD} and average canopy surface height.

For forest vegetation, the first pulse canopy distributions tend to be skewed towards the upper canopy surface, and near ground last returns skewed towards the actual ground surface, often resulting in a bimodal distribution. Short vegetation, however, tends not to display a bimodal distribution (e.g., Hopkinson et al., 2005), and this can be attributed to (*i*) more homogeneous vegetation structure from ground to canopy surface (Cobby et al., 2001); and (*ii*) limitations in older generation lidar sensors preventing first and last LPR separation for ranges below ~4–5 m (Optech Incorporated, personal communication, 2005). In bimodal or skewed unimodal cases, the sample data are not tightly clustered around the mean, and so it is to be expected that the sample σ would be greater than that for a normal distribution displaying the same range, and therefore M describing the relationship between σ and range should be lower.

This study addresses the following research questions:

(1) Can average canopy height (Ht) be estimated as a multiplication factor (M) of the detrended first and last LPR vertical sample distribution standard deviation (L_{SD})? That is, by testing the following hypothesis:

$$\begin{aligned} H_A&:\quad \mathrm{Ht} = ML_{SD} \\ H_0&:\quad \mathrm{Ht} \neq ML_{SD} \end{aligned} \tag{1}$$

(2) If H_0 is rejected, does M vary for bimodal and unimodal LPR distributions (i.e., tall and short vegetation)?

(3) If H_0 is rejected, how do L_{SD} and L_{max} compare for the estimation of average canopy height and Lorey's mean tree height?

Data collection

The airborne lidar and canopy height data presented were collected across the following five study sites (**Figure 1**) within four Canadian forest ecozones: (*i*) a hilly northern Great Lakes (NGL) site in the Turkey Lakes watershed, 60 km north of Sault Ste. Marie (Lim et al., 2003a); (*ii*) a rolling southern Great Lakes (SGL) site within the York Regional Forest, 50 km north of Toronto (Hopkinson et al., 2004a; 2004b); (*iii*) a montane site in the Canadian Rockies (RM) 100 km north of Banff, Alberta; (*iv*) a flat wetland dominated site in the Utikuma Lake area of the Western Boreal (WB) plains of Alberta (Lindsay and Creed, 2005; Hopkinson et al., 2005); and (*v*) a flat valley site near Nictaux in the Acadian forest ecozone of Nova Scotia (NSA), 150 km west of Halifax. Canopy height data were

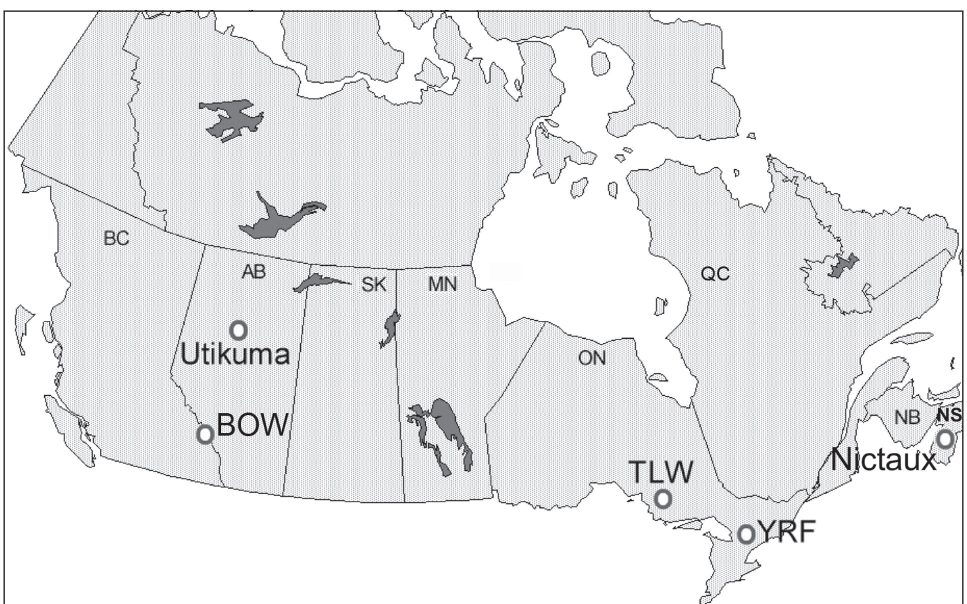

Figure 1. Study site locations within Canada. BOW, Bow Valley; TLW, Turkey Lakes watershed; YRF, York Regional Forest.

collected for the following vegetation cover classes within these five study areas: (1) tolerant hardwood (TH), (2) black spruce (BS), (3) trembling aspen (AS), (4) red pine plantation with no understory (RP), (5) mixed montane pine and fir species (PF), (6) mixed birch and spruce forest (MF), (7) willow shrubs (WS), (8) aquatic marshland vegetation (AQ), (9) grass and herbs (GH), and (10) low shrubs (LS).

All lidar surveys were conducted with airborne laser terrain mapper (ALTM) sensors (Optech Incorporated, Toronto, Ont.) collecting both first and last LPRs with different pulse repetition frequencies (PRF) between sensors (see **Table 1**). Lidar data processing to provide Universal Transverse Mercator (UTM) coordinates (northings, eastings, and elevations) for all first and last LPRs was carried out by the data providers. Due to the ALTM limitation of a minimum range separation between first and last returns, there is a systematic LPR sampling bias for canopy heights below approximately 4 m in height. Canopies above this height tend to display both first (nearer to the canopy surface) and last (nearer to the ground) LPRs, whereas canopies below this height only display single LPRs and are less likely to display a bimodal distribution. For this reason, the vegetation classes investigated have been separated into categories of short and tall vegetation. Classes 6–8 displayed average heights below 2 m and are in the short category. Classes 1–5 displayed average canopy heights above 4 m and were considered tall vegetation. In all cases, the field plots and transects were surveyed using a differential global positioning system (GPS). In all but the NGL plots, the positional error in field GPS data is at the centimetre level. Summary data collection statistics are provided in **Table 1**.

Turkey Lakes watershed (TLW)

Vegetation height data were collected at the TLW study area in July 2000 as described by Lim et al. (2003a). The northern tolerant hardwood (NGL–TH) stands comprise mainly sugar maple (*Acer saccharum* Marsh) and yellow birch (*Betula alleghaniensis* Britton) and were divided into plots of the following three treatment types: natural = untreated (n = 14); selection = uneven-aged silvicultural system in which mature trees have been removed, individually or in small groups (n = 5); and shelterwood = the removal of mature trees in a series of cuttings that extend over a short portion of the rotation to promote even-aged reproduction under the partial cover of seed trees (n = 9). Plots were circular with a radius of 11.3 m (area = 400 m^2) and were georeferenced using GPS with an estimated accuracy of 5 m. Tree heights for all stems with a diameter at breast height (DBH) >9 cm were measured using a Vertex sonic clinometer (Haglof, Madison, Mo.) with an approximate measurement error of up to 1 m for some deciduous trees (Lim et al., 2001). The airborne lidar data collection was carried out in August 2000 using an ALTM 1225 and is described in Lim et al. (2003a). A summary is provided in **Table 1**.

York Regional Forest (YRF)

Two plots were set up in the York Regional Forest (YRF) area. The first was a tolerant hardwood (SGL–TH) plot comprised mainly of sugar maple (*Acer saccharum*) and bitternut hickory (*Carya cordiformis* Wangenh.), similar in character to the NGL–TH plots with no treatment. The second plot was within a mature red pine (*Pinus resinosa* Ait.) plantation (SGL–RP) with uniform upper canopy and no understory. These plots represent endmember canopy structures in the southern Ontario Great Lakes forest ecozone. The associated data collections are discussed in Hopkinson et al. (2004a) and Chasmer et al. (2006). Field data collection was undertaken in September 2000 and July 2002. The plot sizes were 35 m × 35 m (1225 m^2), and mensuration procedures followed those noted for the TLW plots. In addition, the regional geographic information system (GIS) forest resource inventory (FRI) for the entire North Tract was provided by Silv-Econ Ltd. (Newmarket, Ont.) for the purpose of an independent test of canopy height models derived from the LPR data. The regional FRI was compiled over a period of approximately 2–3 years prior to 2000, with stand boundaries delineated by the Ontario Ministry of Natural Resources from aerial photography collected in 1999. Average height was measured using a Suunto optical clinometer from a small selection of trees that were assumed to be representative of each stand. Growth corrections could not be applied to the FRI height data, as the exact dates of measurement for the small selection of stands investigated were not available. Due to the relatively short time period involved, however, it is anticipated that any height differences would be minimal.

Lidar data collection was carried out nine times between September 2000 and November 2004 using various ALTM sensors and a range of survey configurations (**Table 1**). Two summer, or leaf-on, acquisitions (September 2000 and July 2002) were used for the analysis of the tolerant hardwood plot, whereas all nine acquisitions were analyzed for the pine plot. It was expected that the pine plantation would exhibit minimal change in canopy conditions regardless of season. See Hopkinson et al. (2004b) for a description of the first two lidar surveys over the YRF.

Canadian Rockies

Nine plots were set up at 200 m intervals either side of the Icefields Parkway between Banff and Jasper, Alberta, on steep mountain slopes during August 2002. The plots traversed an elevational gradient from 1700 to 2000 m above sea level (asl) within the montane zone. The plots (RM–PF) were dominated by mature Douglas fir (*Pseudotsuga menziesii* Mirb.), subalpine fir (*Abies lasiocarpa* Hook.), and lodgepole pine (*Pinus contorta* Dougl.). The canopies tended to be more open and irregular than those noted earlier. Mensuration followed the same procedures outlined previously, and the plot dimensions were 20 m × 20 m (400 m^2).

Lidar data collection was carried out the week after field mensuration using an ALTM 2050. The general study area and a description of a previous lidar campaign in the area are discussed in Hopkinson et al. (2001). Due to the mountainous

Table 1. Field sampling and lidar sensor configurations.

			Field data				Lidar survey configuration						
Location[a]	Date (month–year)	Terrain	Vegetation type[b]	No. of plots	Plot area (m²)	No. of transects[c]	ALTM sensor model	PRF (kHz)	Sensor altitude (m agl)[d]	Scan rate (Hz)	Scan angle (°)	Avg. point spacing (m)	Data provider[e]
TLW–NGL	08–2000	Hilly	TH	14	400		1225	25	750	15	±15	1.3	Lasermap Image plus
			TH, shelter	9	400								
			TH, select	5	400								
YRF–GL	09–2000	Flat, hilly	TH	1	1225		1225	25	800	30	±12	0.9	Optech Inc.
			RP, plantation	1	1225								
YRF–GL	09–2000	Flat, hilly	TH	1	1225		1225	25	1200	21	±20	1.4	Optech Inc.
			RP, plantation	1	1225								
YRF–GL	12–2000	Flat, hilly	RP, plantation	1	1225		1210	10	700	21	±10	1.3	Optech Inc.
YRF–GL	02–2001	Flat, hilly	RP, plantation	1	1225		1225	25	750	28	±20	1.2	Optech Inc.
YRF–GL	04–2002	Flat, hilly	RP, plantation	1	1225		2050	50	850	44	±15	0.8	Optech Inc.
YRF–GL	07–2002	Flat, hilly	TH	1	1225		2050	50	850	44	±15	0.8	Optech Inc.
			RP, plantation	1	1225								
BOW–RM	08–2002	Steep	Mixed pine–fir	9	400		2050	50	2000–2500	30	±20	2.0	Optech Inc.; C-CLEAR
UTIK–WB	08–2002	Flat	Aspen	4	225		2050	50	1200	36	±16	1.0	Optech Inc.; C-CLEAR
			Black spruce	4	225								
			Willow			2 (16)							
			Mixed shrub			6 (71)							
			Aquatic			4 (49)							
			Grass–herbs			4 (77)							
			No vegetation			1 (95)							
YRF–GL	11–2004	Flat, hilly	RP, plantation	1	1225		3100	33	1000	27	±18	1.0	Optech Inc.
YRF–GL	11–2004	Flat, hilly	RP, plantation	1	1225		3100	50	1000	33	±18	0.9	Optech Inc.
YRF–GL	11–2004	Flat, hilly	RP, plantation	1	1225		3100	100	1000	44	±18	0.6	Optech Inc.
Nict–NSA	08–2004	Flat	MF	5	400		3100	70	800	40	±20	0.7	C-CLEAR
			Grass–herbs			1 (145)							

[a]BOW, Bow Valley; GL, Great Lakes; Nict, Nictaux; NGL, northern Great Lakes; NSA, Acadian forest ecozone of Nova Scotia; RM, Rocky Mountains; TLW, Turkey Lakes watershed; UTIK, Utikuma Lake; WB, Western Boreal plains; YRF, York Regional Forest.
[b]MF, mixed birch and spruce forest; RP, red pine plantation with no understory; TH, tolerant hardwood.
[c]Number of measurements in parentheses.
[d]Metres above ground level.
[e]Canadian Consortium for LiDAR Environmental Applications Research (C-CLEAR), Middleton, N.S.; Lasermap Image Plus, Boisbriand, Que.; Optech Incorporated, Toronto, Ont.

nature of the study site, the survey altitude and laser pulse density over the plots varied (see **Table 1**).

Utikuma Lake

Utikuma Lake was the only survey site where both short vegetation and forest categories were sampled. Four 15 m × 15 m (225 m^2) plots were set up of trembling aspen (*Populus tremuloides* Michx.) (WB–AS) and four of black spruce (*Picea mariana* Mill.) (WB–BS), as they are representative of deciduous and coniferous species of the western boreal forest ecozone. Mensuration of the aspen plots followed the same methods as outlined earlier. However, applying a >9 cm DBH rationale to the measurement of tree height in the black spruce plots was impractical, as a high proportion of stems had a DBH of <9 cm and still made up a significant part of the canopy surface. Therefore, all stems above 2 m in height were measured to ensure that all major canopy elements were included in the samples (Hopkinson et al., 2005).

An ALTM 2050 lidaShort vegetation was measured at intervals of 0.5–2.0 m along transects of 30–65 m in length. The height of the mean maximum vegetation surface (canopy height) within 0.5 m of every GPS-surveyed transect point was visually approximated and measured with a measuring staff (measurement error up to 0.1 m). In areas of variable canopy height, three measurements were taken and the mean was recorded as shown in **Figure 2**. Vegetation along each transect was classified according to the Ducks Unlimited Canada (2002) land cover classification scheme into aquatic vegetation (WB–AQ), grass and herbs (WB–GH), low shrubs (WB–LS), and tall shrubs (WB–WS). Willow shrub (WB–WS) vegetation (genus *Salix*) was classified as tall shrub, and the mean height was above 4 m for each transect and therefore representative of tall vegetation. Willow canopy heights were estimated by extending the survey staff into the canopy (measurement error up to 0.3 m). Given the small area coverage (<1 m^2) of each individual transect canopy height measurement, all height measures were combined and averaged per transect. For the three short vegetation classes (AQ, LS, and GH) none of the height measurements exceeded 2 m.r survey was carried out coincident with field data collection in late August 2002. The study area was surveyed with 50% side lap between flight lines, effectively providing 200% data coverage and a dense LPR distribution on the ground of up to five pulses per square metre (Hopkinson et al., 2005).

Nictaux

Five 11.3 m radius mixed forest (MF) plots were set up within uneven-aged natural regeneration areas near Nictaux in the Annapolis Valley of Nova Scotia. The plots comprised predominantly yellow birch (*Betula alleghaniensis*), with occasional pine (*Pinus*) and spruce (*Picea*) trees interspersed throughout. An additional 60 m long grass transect was traversed across a hay field to provide additional data for the short vegetation component of the study. Field mensuration took place in August 2005 and was carried out as noted earlier. Lidar data collection was carried out within 2 weeks of all field mensuration using an ALTM 3100 (**Table 1**).

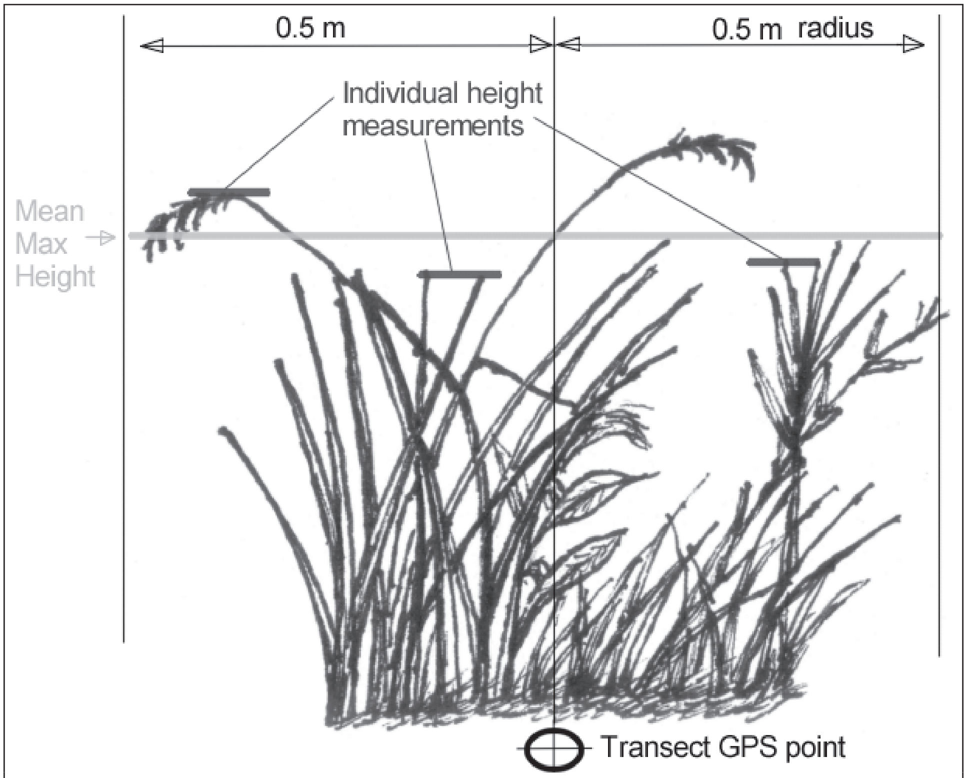

Figure 2. Method of estimating short vegetation canopy height along transects.

Analysis

Airborne GPS trajectory, ground GPS base station, on-board inertial reference system, scan angle, and raw laser range data were combined within the Optech REALM software to generate UTM coordinates for every first and last LPR collected over the study areas. The service providers classified LPRs into ground and vegetation using proprietary filtering techniques (e.g., Raber et al., 2002). The ground returns from all surveys were interpolated to a 1 m raster DEM of the ground beneath the vegetation canopy using an inverse distance weighted algorithm (Lloyd and Atkinson, 2002). The data were then topographically detrended by subtracting the corresponding heights of the ground DEM from all LPRs. This procedure removed the influence of topography and resulted in LPR heights that were now measured relative to ground height. Some interpolation error is expected in the lidar DEMs, but this is expected to be at the centimetre to decimetre level (e.g., Töyrä et al., 2003; Hodgson and Bresnehan, 2004; Hopkinson et al., 2005) and of negligible influence to the calculation of L_{SD}.

Using the field-measured GPS coordinates, the detrended LPR data corresponding to each field plot and transect were isolated so that L_{SD} and L_{max} could be calculated. Average plot and transect canopy heights were regressed against the corresponding L_{SD} and L_{max} for short vegetation classes (≤2 m), tall vegetation classes (≥4 m), and all vegetation (unfortunately, none of the classes sampled fell in the range 2 m to >4 m). For tall vegetation, L_{SD} and L_{max} were also compared with plot-level Lorey's mean tree height.

A comparison of the derived L_{SD} and L_{max} canopy height regression models was made using independent FRI data from a 1.5 km × 1.0 km area within the YRF. This area was selected because it contained 19 stands of conifer and deciduous species displaying variable height characteristics, 12 of these having at least 90% of their area fully within the study area. Within the area selected there were also hay fields that had not been included in the FRI but were noted on the ground at the time of the September 2000 survey to be approximately 1 m in height. The FRI height data were converted from stand-level polygons to a raster grid. Grid cells of 50 m × 50 m were chosen, as the stand boundaries have an error of ±20 m in places, and this resolution provides enough grid cells for meaningful analysis ($n = 297$). This approach inevitably leads to mixed cells at stand boundaries, but a higher resolution would not improve the analysis because it would lead to a greater number of misclassified cells. Most grid cells were located over mature forest stands, biasing the sample distribution towards tall canopy heights and therefore introducing heteroscedacity. To remove heteroscedacity, the sample data were systematically thinned to provide an even distribution of FRI heights ($n = 38$), and the regression analysis was performed again.

Results and discussion

Establishing the *M* factor

Examples of ALTM first and last LPR frequency distributions from canopy to ground level for each vegetation class studied are presented in **Figure 3**. The height and frequency axes are presented as percentiles (10% increments) to enable direct comparison of each vegetation class LPR distribution, regardless of height or number of pulses. For tall vegetation classes (**Figure 3A**), it is apparent that the sample distributions tend to be bimodal, with modes at canopy and ground level. The relative magnitude of each of these modes will depend somewhat on canopy openness and laser pulse penetration through the canopy. Of note, however, is that one tall vegetation class, Rockies montane (RM–PF), does not display a distinct bimodal distribution in the example provided. Such distributions are weighted downwards due to increased ground- and low-level canopy returns as a result of these plots containing a sparse tree coverage displaying various heights with no uniform upper canopy surface. For the short vegetation transects sampled (**Figure 3B**), the LPR distributions from ground to canopy display a single strong mode. All vegetation classes display at least one dominant mode with a frequency ranging between 15% and 50% of all LPR data within the vertical distribution.

For the short vegetation transect data (**Figure 4**), the null hypothesis of no relationship between mean maximum canopy height and L_{SD} can be rejected at the 99% confidence level. The M factor relating L_{SD} to short vegetation canopy height is 2.7, with 75% of the variance explained by the linear regression model (if the slight outlier to the right of **Figure 4A** is removed, M remains at 2.7 but the coefficient of determination r^2 reduces to 0.55). This result is comparable with that of Cobby et al. (2001), in that their r^2 of 0.8 and RMSE of 0.14 m are similar to the findings here. However, the relationship established between Ht and L_{SD} by Cobby et al. was logarithmic, predicted Ht to be less than L_{SD} at around 4 m above the ground, and therefore has a range of application that is limited to Ht < ~2 m. For the results presented in **Figure 4A**, logarithmic regression returned an r^2 of 0.70 with an RMSE greater than 0.2 m and was considered unsatisfactory compared with the linear model. A linear model was also favoured here because it has the potential to be useful for a wider range of Ht values, i.e., for both short and tall vegetation. The same analysis applied to L_{max} resulted in slightly poorer results, with only 49% of the variance explained and an RMSE of 0.23 m (**Figure 4B**).

A limitation of the application of a simple multiplier of L_{SD} for the estimation of canopy height is that for small values of L_{SD}, there will always be a positive value for Ht due to the inherent noise in the lidar data. From Hopkinson et al. (2005) it was found that for lidar data collected over flat unvegetated ground, L_{SD} was approximately 0.07 m. This would therefore lead to a minimum Ht value of ~0.19 m if the M factor of 2.7 were applied to areas of very short or no vegetation. Another difficulty is that L_{SD} will tend to increase in areas of steep slope, regardless of vegetation height, as a result of lidar positional inaccuracy (Hodgson and Bresnehan, 2004). For such sloping areas it might be possible to adjust *M* downwards based on the angle of slope in the ground DEM. Unfortunately, the influence of slope on *M* was not quantified due to the methodological necessity for flat areas to enable controlled L_{SD} and Ht measurements for the short vegetation classes. Fortunately, however, the influence of noise and slope to L_{SD} diminish as vegetation height increases and are likely insignificant components of L_{SD} for the tall vegetation classes.

For the 57 tall vegetation plots, the null hypothesis of no relationship between average height and L_{SD} was rejected at the 99% confidence level. The *M* factor relating L_{SD} to Ht was slightly lower (2.5) than that for short vegetation (2.7), with 85% of the variance explained by the linear regression model (**Figure 5A**). However, this difference in *M* was not statistically significant. After plotting all short and tall vegetation together, it was found that $M = 2.5$ ($r^2 = 0.95$, $n = 77$, RMSE = 1.8 m). As with short vegetation, the analysis yielded slightly poorer results for L_{max} (**Figure 5B**), but the multiplier of 0.73 was also not statistically different from the short vegetation analysis result of 0.75. It is worth noting that in **Figure 5A** most of the data plot close to the regression line, with the exception of NGL–TH. If the NGL–TH data are removed from the analysis, the RMSE improves to 1.3 m.

Increased spread around the regression line in the NGL–TH data could be related to imprecise field GPS data, leading to relatively poor colocation of field and lidar plots. Of note, however, is that different TH treatments scatter either side of the regression line, with the height of natural plots underestimated and shelterwood treatments overestimated. This difference in L_{SD} height estimation could be due to (*i*) different LPR distribution properties in each of the treatment types leading to a change in *M*, or (*ii*) an overestimation of the plot-level average height due to the omission of smaller trees in the plots. Certainly, the >9 cm DBH measurement method for the NGL plots would ignore the influence of smaller trees in the plot and result in an overestimation of average plot-level height. This effect would be less apparent in natural plots where the canopy is comprised almost exclusively of mature trees but enhanced in the shelterwood treated plots where mature trees have been removed. The possibility of a canopy structure type dependent *M* factor must also be considered, as 11 of the 14 natural TH plot heights and four of the five natural MF plot heights from the NGL, SGL, and NSA locations plot above the Ht versus L_{SD} regression line (**Figure 5**). However, the data available for this study are insufficient to enable quantification of the subtle differences in *M* due to vegetation canopy structure.

In this study, L_{SD} has been compared with average canopy height, whereas some studies have focused on the relationship between LPR distribution metrics and plot-level Lorey's height (e.g., Naesset, 1997; Magnussen and Boudewyn, 1998). From the lower RMSE (2.1 m compared with 3.0 m) and increased explanation of the variance ($r^2 = 0.80$ compared with 0.59) in **Figure 6A**, it appears that for the data used in this study L_{SD} is a better estimator of average canopy height than Lorey's mean tree height. This is probably because L_{SD} is related to the entire vegetation column and is influenced by the ground and canopy

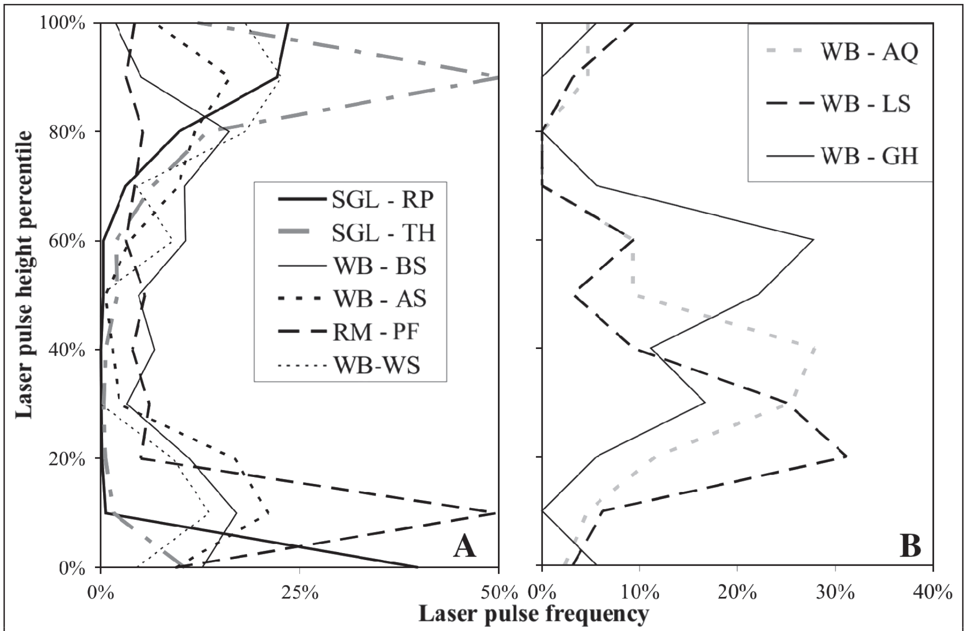

Figure 3. Vertical LPR distributions for a range of vegetation classes: (A) tall vegetation (≥4 m) with possibility of dual pulse returns; (B) short vegetation (<2 m) with only single LPRs. AQ, aquatic marshland vegetation; AS, trembling aspen; BS, black spruce; GH, grass and herbs; LS, low shrubs; PF, mixed montane pine and fir species; RP, red pine plantation with no understory; RM, Rocky Mountains; SGL, southern Great Lakes; TH, tolerant hardwood; WB, Western Boreal plains; WS, willow shrubs.

frequency distribution modes, whereas Lorey's height is related to dominant trees in the canopy and therefore the upper tail of the LPR distribution. This is further evidenced in the observation that L_{max} appears to be a better indicator of Lorey's mean tree height than L_{SD} (**Figure 6B**). These results suggest that LPR metrics that are biased towards the upper limits of the LPR distribution might be appropriate if tall elements in the canopy are of interest; however, if mean canopy surface height is of primary interest, then a metric that is based on the entire LPR distribution such as L_{SD} might be more appropriate.

Testing the *M* factor

Grids of independent FRI Ht and L_{SD}-derived Ht for the North Tract of the YRF are illustrated in **Figure 7**. The most obvious difference between the two grids is that the L_{SD} heights are more spatially variable. This is to be expected, as the FRI stand polygons are colour coded to average stand height and provide no information on within-stand variation, whereas the L_{SD} heights are calculated on an individual grid cell basis. There are some similarities in the two grids, namely some of the shorter vegetation polygons are clearly discernible in both,

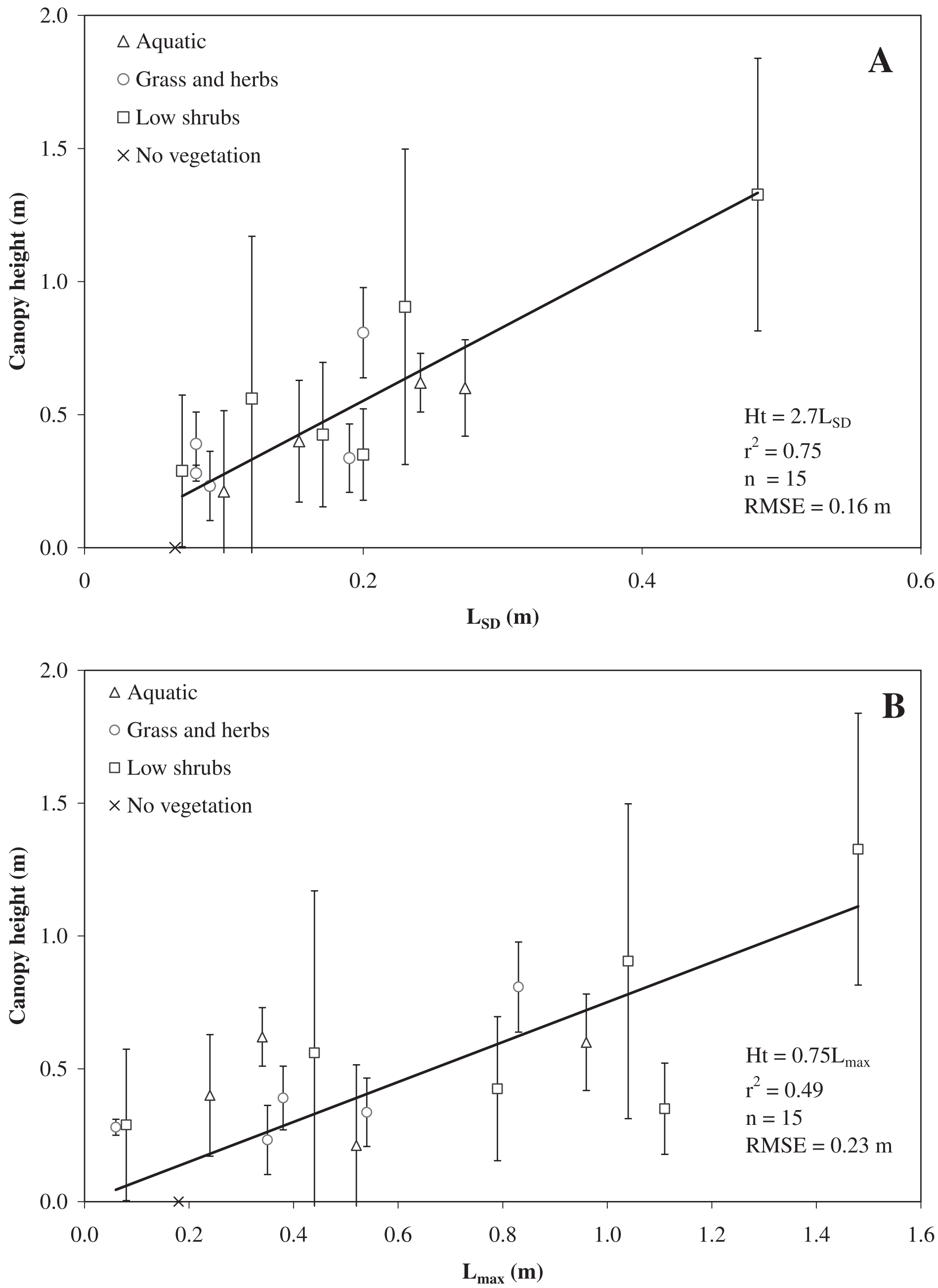

Figure 4. Short vegetation canopy heights (<2 m) plotted against (A) LPR distribution standard deviation (L_{SD}), and (B) LPR distribution maximum height (L_{max}). Error bars denote standard deviation in transect height measurements.

and the overall average heights are similar. However, the heights of the tallest FRI stands have been underestimated in the L_{SD} height grid. Of note is that the tallest stands are of the tolerant hardwood (TH) class and are similar in canopy characteristics to the NGL and SGL TH plots investigated. It is apparent from **Figure 5** that the TH natural plot data lie slightly above the regression line, suggesting that a slightly higher *M* factor would be more appropriate for this class.

The almost 1:1 relationship between independent grid cell FRI data and L_{SD}-modelled vegetation heights in **Figure 8A** suggests that the *M* factor of 2.5 established from the training datasets is appropriate when dealing with several different vegetation heights and classes. It can be argued that, with an RMSE of 4.7 m and only a 73% explanation of the variance, this simple model is of limited value. However, it also needs to be noted that the FRI data used for this test were collected prior to the lidar data and were imprecisely collected compared to the training data used, and the 50 m cell size probably introduced additional random error due to stand edge effects. Bearing these factors in mind, a high RMSE and intermediate r^2 would be expected. As with the training data collected from various sites across Canada, FRI stand heights predicted using the L_{max} model (**Figure 8B**) demonstrated a higher RMSE (8.2 m) and a lower explanation of the variance (58%).

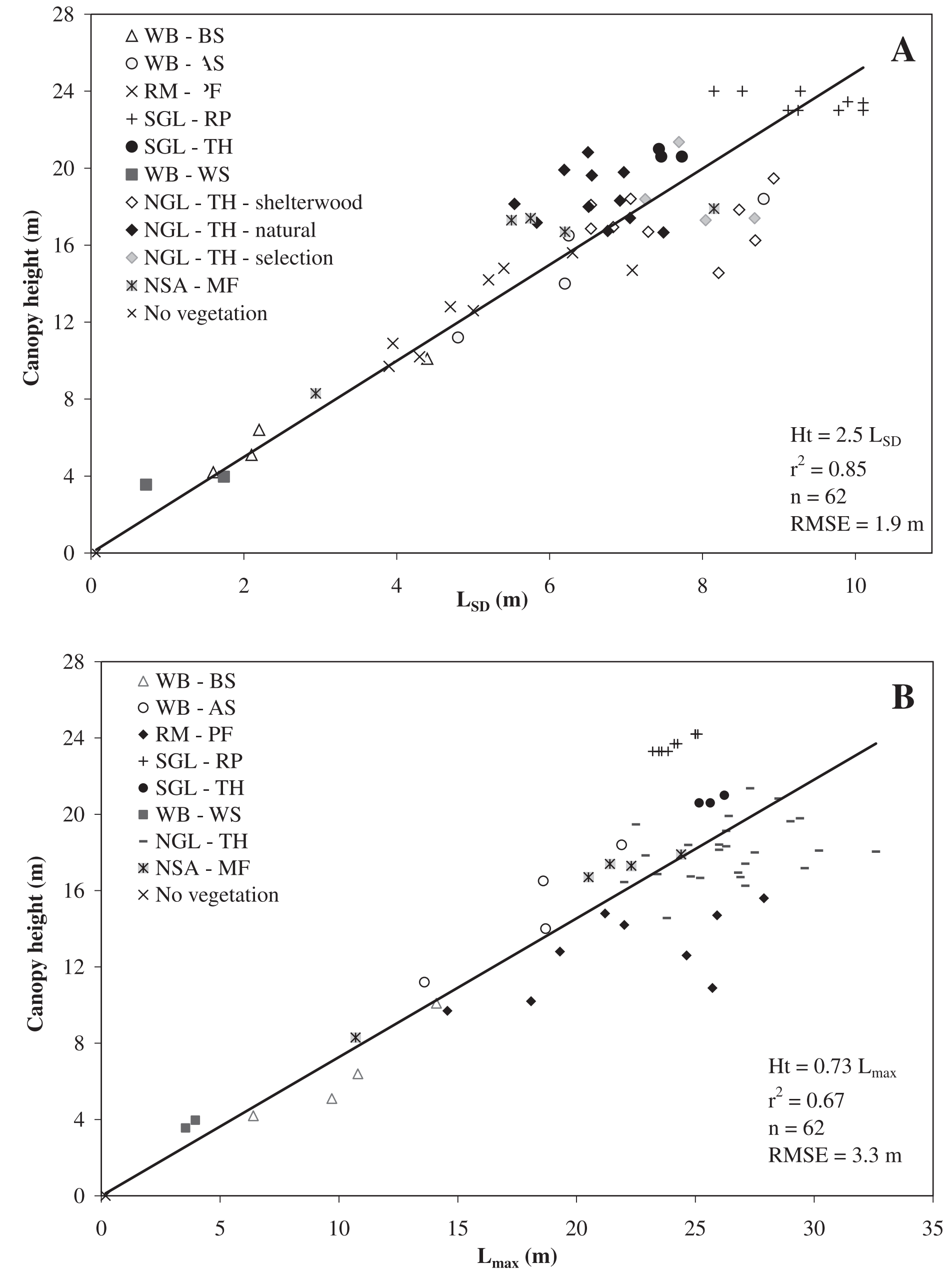

Figure 5. Plot-level average canopy heights for tall (≥4 m) willow and forest classes plotted against (A) LPR distribution standard deviation (L_{SD}), and (B) LPR distribution maximum height (L_{max}). Legend abbreviations as in **Table 1** and **Figure 3**.

Conclusions

It has been demonstrated that the mean canopy surface height for combined aquatic, grass–herb, and low shrub classes of short vegetation (all < 2 m in height) can be estimated using a simple multiplier (*M* factor) of the vertical laser pulse return (LPR) distribution standard deviation (L_{SD}). For tall vegetation classes (>4 m) the average canopy height calculated from all individual stem height measurements was also related to L_{SD}. *M* was 2.7 and 2.5 for short and tall vegetation, respectively, but was 2.5 when all data were combined ($r^2 = 0.95$, $n = 77$, RMSE = 0.18 m, $p < 0.01$). For forest vegetation, L_{SD} and Lorey's mean tree height were not well correlated. This was considered due to Lorey's height being a function of dominant canopy elements, which should be represented in the upper tail of the canopy distribution, whereas L_{SD} is sensitive to the high-frequency modes within the entire distribution from canopy to ground. Lorey's mean tree height was better estimated using the localized maximum height of the vertical LPR distribution (L_{max}).

Although there are numerous other LPR distribution estimators of canopy height, L_{SD} is useful in that it is a function of the overall distribution shape from ground to canopy and, provided there is a sufficient number of laser pulses in the area

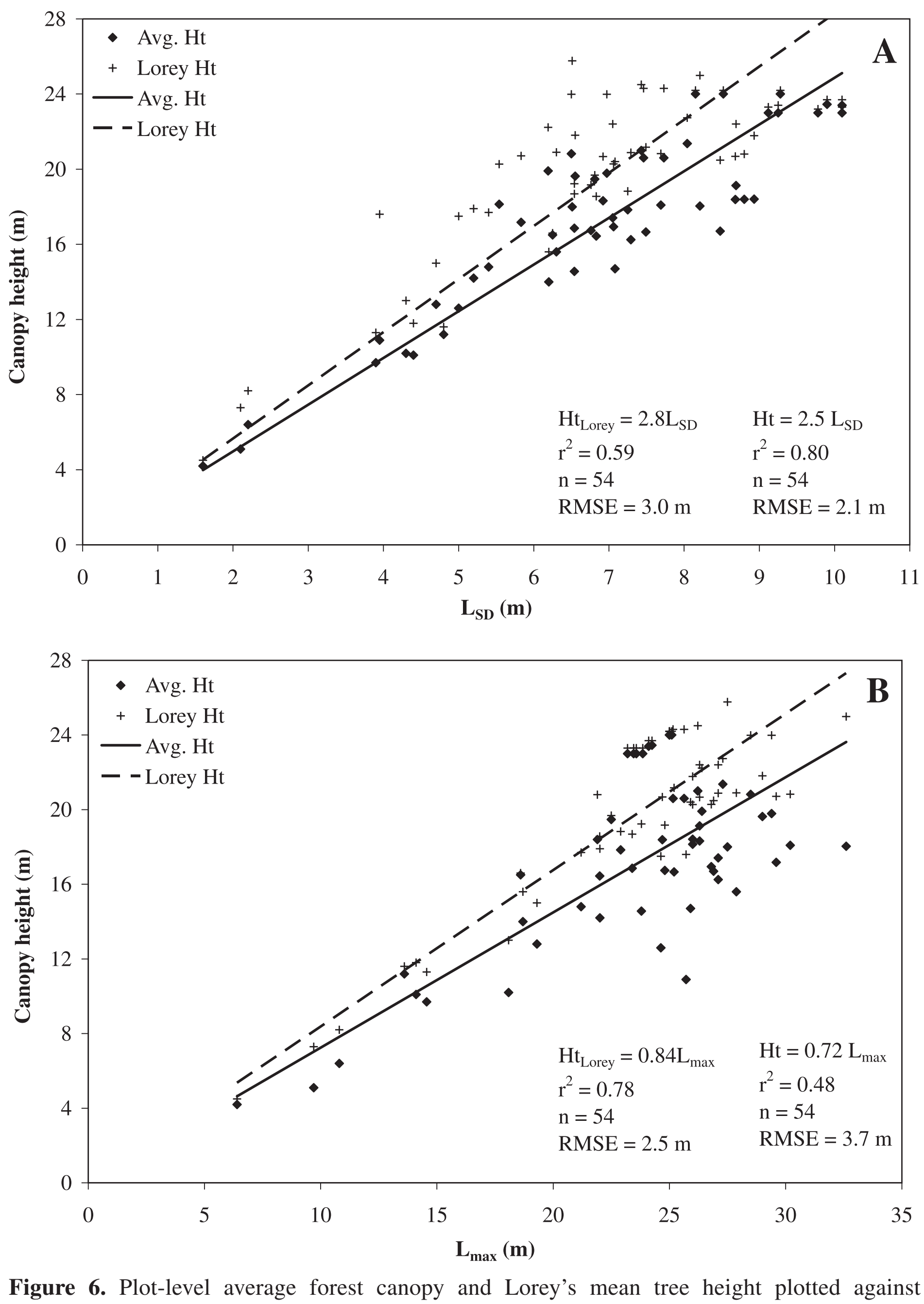

Figure 6. Plot-level average forest canopy and Lorey's mean tree height plotted against (A) LPR distribution standard deviation (L_{SD}), and (B) LPR distribution max height (L_{max}).

of interest, is insensitive to LPR density. Grid-based maximum LPR height (L_{max}), although potentially better than L_{SD} after calibration and on an individual data collection basis, varies with LPR sample density and crown morphology and therefore cannot be universally applied with the same expectation of accuracy.

The average *M* factor of 2.5 slightly underestimates the heights of hardwood species in both the training data and the model, and so there probably is some vegetation-class dependence to the *M* factor, i.e., a larger value for *M* seems appropriate for vegetation with canopy characteristics similar to those of the TH and MF classes. As a robust first approximation to mapping canopy height over large areas of varying height and vegetation type, however, an *M* factor of 2.5 provides reasonable results. The advantages of using a multiplier of L_{SD} to estimate average canopy height are as follows: (*i*) it has a wide application to a range of vegetation types and height classes and lidar data collection configurations; and (*ii*) it is based on the statistical property that a sample range can be related to its standard deviation. To make

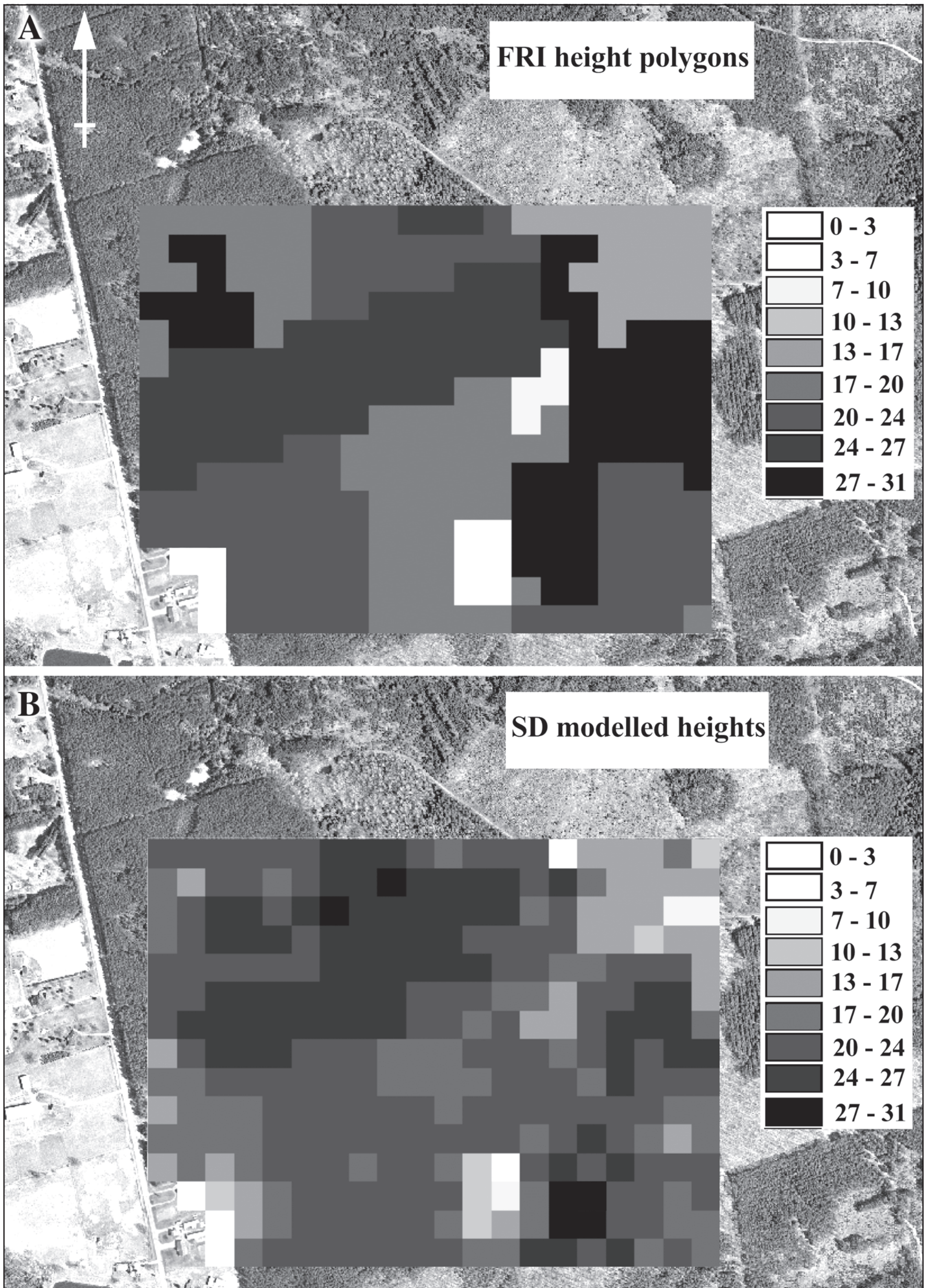

Figure 7. FRI Ht grid (A) compared with L_{SD} Ht model grid (B). Grid cell average heights are in metres.

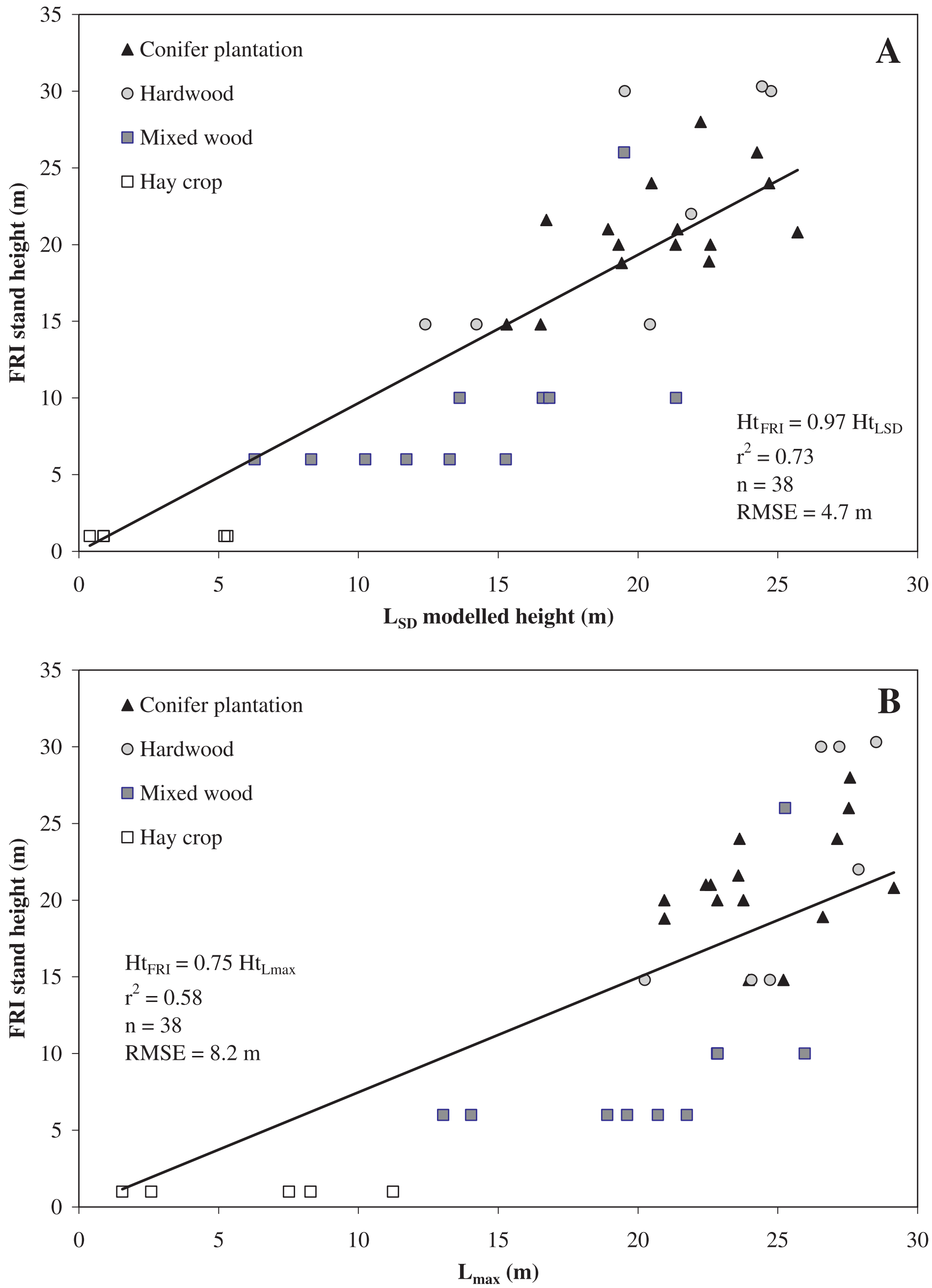

Figure 8. Vivian forest grid cell modelled heights for the September 2000 low-altitude survey: (A) FRI versus L_{SD}; (B) FRI versus $L_{max.}$ FRI data >14 m height thinned to remove heteroscedacity.

the L_{SD} M factor of practical use in canopy height mapping applications across multiple lidar datasets and environments, further study is needed to quantify the subtle variations in M with vegetation structural characteristics, terrain slope, and different lidar sensor technologies.

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