Stability of sample-based scanning LiDAR-derived vegetation metrics for forest monitoring

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Pre-print of published version.

Reference:
Bater, C.W., Wulder, M.A., Coops, N.C., Nelson, R.F., Hilker, T., Næsset, E., 2011. Stability of sample-based scanning-LiDAR-derived vegetation metrics for forest monitoring. Transactions on Geoscience and Remote Sensing 49, 2385–2392.

To link to this Article: DOI: http://dx.doi.org/10.1109/TGRS.2010.2099232

URL: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5696751&tag=1

Abstract
The objective of this research is to gain insights into the reproducibility of LiDAR-derived vegetation metrics for multiple acquisitions carried out on the same day, where we can assume that forest and terrain conditions at a given location have not changed. Four overlapping flight lines were flown over a forested area on Vancouver Island, British Columbia, Canada. Forty-six 0.04 ha plots were systematically established and commonly derived variables were extracted from first and last returns, including height-related metrics, cover estimates, return intensities, and absolute scan angles. Plot-level metrics from each LiDAR pass were then compared using multivariate repeated measures analysis of variance (ANOVA) tests. Results indicate that while the number of returns were significantly different between the four overlapping flight lines (F (3, 43) = 28.99, p <<0.05), most LiDAR-derived first return vegetation height metrics were not. First return maximum height (F (3, 43) = 3.11, p = 0.04) and overstorey cover (F (3, 43) = 4.27, p = 0.01), however, were significantly different and varied between flight lines by an average of approximately 2% and 4%, respectively. Scan angles were not found to impact the plot-based forest attribute estimates. First return intensities differed significantly (F (3, 43) = 61.78, p << 0.05) between over-passes where sudden changes in the metric occurred without any apparent explanation; intensity should only be used following calibration. With the exception of the standard deviation of height, all second return metrics were significantly different between flight lines. Despite these minor differences, the study demonstrates that when the LiDAR sensor, settings, and data acquisition flight parameters remain constant, and time-related forest dynamics are not factors, LiDAR-derived metrics of the same location provide stable and repeatable measures of forest structure, confirming the suitability of LiDAR for forest monitoring.

Keywords:

LiDAR, laser altimetry, sampling, monitoring, forest, vegetation, multi-temporal, Canada

Introduction
Light detection and ranging (LiDAR) is a remote sensing technology rapidly gaining acceptance as a survey tool capable of providing accurate, high spatial resolution, three dimensional information regarding forest structure. LiDAR has a demonstrated capacity to support forest inventory [1]-[5], monitoring and change detection [6]-[8], and habitat mapping [9]-[12]. With the increasing use of LiDAR data, the design of surveys balancing information content with cost efficiency has become an area of active research.

A number of studies have addressed the issue of LiDAR survey efficiency by varying flight and sensor parameters, and then examining the effects on the accuracies of derived metrics and biophysical estimates[13]-[20]. For example, an investigation of the effects of platform altitude, scan angle, and footprint size found that the relative plot-level vertical distribution of LiDAR returns remained stable even when flying heights where varied [15]. A study testing the influence of altitude, beam divergence, and pulse repetition frequency (PRF) on the distribution of LiDAR metrics in forested canopies found some decimetre-level changes in canopy penetration, many of which were statistically significant at the 90% level; however, considerable manipulation of flying height or PRF was necessary to obtain these results [16]. An investigation of the effects of different sensors, flying altitudes, and PRFs on LiDAR-derived metrics and biophysical properties found that both the canopy height distribution and pulse penetration were influenced by the survey configuration, and demonstrated that the combined effects of vertical shifts in the canopy height distribution and changes in penetration can cause systematic shifts in timber volume predictions on the order of approximately 10% [20]. Furthermore, the height distributions of last return data were more sensitive to changes in the survey parameters than were first returns. Reference [20] also provides a discussion integrating the results from, and implications of, the previously mentioned research and raises several important issues: first, that it can be difficult to compare the relative importance of survey parameters as different studies employ different experimental designs and are carried out in dissimilar forest environments; and second, that in many studies the results are confounded by an inability to isolate a given effect.

While the previous research makes valuable contributions to the optimization of LiDAR surveys for vegetation-related data collection, a key assumption is that a given set of parameters will produce repeatable measurements. The objective of this research is to investigate the capacity of LiDAR to accurately capture forest structure in a repeatable fashion when there is no change in forest stand characteristics (i.e. disturbance or growth), and when survey design is held constant. To do so, we test the reproducibility of commonly employed LiDAR-derived forest metrics by comparing data collected on the same day with identical survey parameters.

Methods

Study area

The study area is located on the Saanich Peninsula on the east coast of Vancouver Island, British Columbia, Canada. Falling within the rain shadow created by the leeward located mountains on Vancouver Island, the area is classified as coastal Douglas-fir according to British Columbia's biogeoclimatic classification system [21]. The coastal Douglas-fir zone is the smallest in the province, generally occurring below 150 m and occupying approximately 260,000 ha of British Columbia. The coastal Douglas-fir zone is characterized by a relatively dry climate for the area, a history of frequent but low-intensity fires, and the presence of Douglas-fir (*Pseudotsuga menziessii* (Mirb.) Franco) as the dominant tree species [22].

The transect consists mostly of multiple cohort mature forest covering rugged, glacially scoured terrain. Elevations range from approximately 70 to 250 m above sea level. Douglas-fir is the dominant species, with western redcedar (*Thuja plicata* (Donn ex D. Don) Spach) occurring as a co-dominant or subdominant species throughout, and red alder (*Alnus rubra* (Bong.) Carr.) occupying low moist sites. Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), arbutus (*Arbutus menziesii* Pursh), and black cottonwood (*Populus trichocarpa* Torr. & Gray) also occur in small numbers.

LiDAR data acquisition and processing

Four overlapping LiDAR swaths were collected along a 3-km forested transect on 17 October 2008 with identical sensor and survey parameters. Small footprint laser data were collected by Terra Remote Sensing Inc. (TRSI) (Sidney, British Columbia, Canada), using TRSI's Mark II two-return sensor onboard a fixed-wing platform. The instrument employs a single sensor capable of recording both first and last returns, and the survey was optimized to achieve a nominal first return density of approximately two returns/m^2 (Table 1). The area of overlap between the four swaths varied in width from approximately 140 to 180 m.

Insert Table 1 about here

First and last returns were classified as ground or non-ground by the vendor using Terrascan software [23]. Four 1 m spatial resolution digital elevation models (DEMs) were then generated by rasterizing each flight line's ground returns using a natural neighbour algorithm [24], [25]. To reference non-ground returns to their heights above the ground, DEM elevations were subtracted from the ellipsoidal heights of the non-ground returns, and the lower limit of vegetation cover was then defined using a threshold value of 1 m above the ground.

A series of circular virtual plots were established within the area of overlap between the four flight lines using a systematic sampling design and a 90 m sampling interval (Fig. 1); in total, 46 plots fell within forested areas of the transect. The plots were 400 m^2 in size, which conforms to Canadian National Forest Inventory standards for ground-based large tree assessment [26]. A comparison of the plot-level lidar metrics between the four flight lines formed the basis of our analyses, eliminating the need for detailed field mensuration data.

Insert Fig. 1 about here

A number of plot-level variables were extracted from the LiDAR vegetation data based on previous research demonstrating their relationship with vertical structure. When analyzing vegetation metrics, first and last returns were treated separately, as they have been shown to have different characteristics [15], [20].

Terrain heights

All height-related vegetation metrics are based on their height relative to the ground, which is in turn modeled using the DEM generated for each overpass. To ensure that the stability of the metrics was not affected by differences in the terrain height surfaces, differences between the plot-level mean and standard deviation of the DEMs were examined.

First return data

Vegetation metrics calculated from the first return data included the 10, 25, 50, 75, 90, 95, and 99 percentiles [27]-[30]; the mean, maximum, standard deviation, skewness, kurtosis, and coefficients of variation of vegetation return heights [28], [31], [32]; and two cover estimates, or the ratios of first returns above a given height to the total number of first returns (including those classified as ground) within each plot [15], [33], [34]. The cover metrics included understorey cover, which was defined as 0.5-3m above the ground, and overstorey cover, defined as greater than 3 m above the ground. Note that the understorey cover metric was the only variable including vegetation returns below the 1 m height threshold. The total number of returns, the number of first returns, and intensity values were also examined. Finally, absolute scan angles were compared. Although not a forest metric, differences in scan angles between overpasses would indicate that flight profiles were not reproduced as intended. Additionally, observing scan angle in conjunction with the forest metrics provides insights on the repeatability of the lidar metrics as a function of survey conditions.

Last return data

Vegetation metrics calculated from the last return data included the 25, 50, 75, and 95 percentiles; the mean, maximum, standard deviation, skewness, kurtosis, and coefficient of variation of return heights, return intensity, and the number of last returns above the 1 m height threshold.

Statistical analyses

Analysis of variance (ANOVA) employing a repeated-measures design was used to test for differences in the plot-level metrics calculated from the four overpasses. Repeated measures designs are appropriate when numerous measurements are made on the same subjects over time [35], which in this case were the 46 forest plots. Unlike a one-way ANOVA, repeated measures designs are not restricted by the assumption of homogeneity of variance. However, sphericity or circularity, which refers to the equality of the variances of the differences between treatment levels, is a critical assumption that must be met when employing standard univariate F tests. When the assumption of sphericity is violated, a multivariate approach which simultaneously tests the statistical significance of the contrasts between repeated measures may be employed [35]. Using the repeated measures ANOVA, the following hypotheses were tested for each LiDAR metric:

H_o: No difference exists between metrics derived from different LiDAR passes.
H_a: A difference exists between metrics derived from different LiDAR passes.

Accepting the null hypotheses would indicate that the LiDAR metrics in question are robust and repeatable estimates of forest structure. For those metrics where the null hypothesis was rejected, Bonferroni post-hoc comparisons were used to examine the statistical significance of the differences between means for the flight line pairs.

Results

The results of the repeated measures ANOVA analyses are reported in Table 3. Mauchly's tests for sphericity indicated that the majority of variables violated this assumption, and as a result multivariate F tests were employed. Although the four overlapping flight lines were specified to be flown using identical flight and sensor parameters, the number of returns found within each plot varied between flight lines (Table 2). The flight lines contained an average of 2327, 3345, 2944, and 4309 returns per plot for flight lines 1 to 4, respectively. The proportion of returns that were first returns, however, were similar for all flight lines, ranging from 81-87% (Table 2), as were the vertical distributions of first and last returns within plots (Fig. 2). An examination of the possible impact of scan angle on the ratio of first returns to last returns showed no obvious effect.

Insert Table 2 about here

Insert Fig. 2 about here

Terrain heights
Individual DEMs were created for each flight line. Plot-level modeled terrain heights were not significantly different between flight lines (Table 3), a critical result as the vegetation metrics were directly related to the lidar return heights above the surfaces. For example, within the plots, mean terrain height varied by approximately a decimeter between lines (F (3, 43) = 2.63, p = 0.06).

First return data
As mentioned above, the total number of returns and the number of first returns within plots were significantly different between flight lines. This result, however, did not impact most of the derived first return vegetation height metrics. The differences in the repeatedly estimated height metrics, including mean, standard deviation, coefficient of variation, and the 10, 25, 50, 75, 90, 95 and 99 percentiles, were small and not statistically significant (Fig. 3). For example, plot-level differences between first return mean height, coefficient of variation of height, and the 95th height percentile were 3%, 4%, and 2%, respectively, and correspond to decimetre-level discrepancies. Maximum height was weakly but significantly different between flight lines (F (3, 43) = 3.11, p = 0.04). Nonetheless, plot-level differences averaged only approximately 2%, or less than one metre, and a Bonferroni post-hoc pair-wise comparison indicated that the flight lines were not significantly different. Understorey cover estimates were not significantly different (F (3, 43) = 2.40, p = 0.08). Overstorey cover estimates were found to be significantly different (F (3, 43) = 4.27 , p = 0.01) and varied by approximately 4% between flight lines (Fig. 3). A Bonferroni post-hoc pair-wise comparison indicated that flight lines 1 and 2 were significantly different from flight line 3.

Insert Table 3 about here
Insert Fig. 3 about here

The mean and standard deviation of laser pulse intensities were strongly and significantly different (e.g. for mean intensity F (3, 43) = 61.78, p <<0.05) and varied by approximately 17% between plots. A Bonferroni post-hoc pair-wise comparison indicated that intensities between flight lines 1 and 2 were not significantly different, nor were those between flight lines 3 and 4; however, flight lines 1 and 3, 1 and 4, 2 and 3, and 2 and 4 were significantly different. A visual examination of the interpolated intensities showed a sharp drop in values at the midpoint of flight line 3 which continued to flight line 4. This drop in intensity values explains the increased variance within plots for flight line 3. Mean intensity remains low in flight line 4, but the variance stabilizes to levels similar to those present in flight lines 1 and 2 (Fig. 3). Finally. absolute scan angles, which varied from 0-15 degrees, where not significantly different between flight lines, indicating that the flight profile was consistent during the survey (Table 3, Fig. 3).

Last return data
The results of the repeated measures ANOVA analyses indicated that, with the exception of the standard deviation of the last return heights, all variables were significantly different (Table 3). Last returns represented a small proportion of the vegetation returns in the plots, ranging from 7% - 11%, and their numbers were significantly different between flight lines (F (3, 43) = 10.90, p <<0.05). The plot-level mean and maximum heights and the height percentiles varied on

average by more than a metre between different flight lines (Table 3). Plot-level differences between last return mean height, coefficient of variation of height, and the 95th height percentile were 10%, 11%, and 6%, respectively. The mean and standard deviation of last return pulse intensities were also significantly different (e.g. for mean intensity F (3, 43) = 42.26, p <<0.05). Bonferroni post-hoc pair-wise comparisons revealed no consistent trend in differences between flight lines.

Discussion

The objective of this study was to test the reproducibility of common LiDAR-derived metrics by examining the random errors associated with multiple scans of the same location. Although forest structure in the study area was complex, it was relatively similar across the transect, and the results presented here may be specific to this forest environment. Forests with different characteristics may require the utilization of different LiDAR survey parameters to ensure that derived metrics are reproducible. Further, when undertaking the acquisition of LiDAR data for forest characterization, a second overpass over a previously scanned area could be considered to demonstrate the consistency of the measures produced.

For the first return data, with the exception of maximum height and overstorey cover, the majority of height-related metrics were not significantly different when tested using a repeated measures ANOVA. For maximum height, the ANOVA results were only weakly significantly different, and a post-hoc comparison found no significant differences, likely because actual shifts in maximum height between flight lines were small. Observed differences were typically less than one metre, which is of a magnitude equivalent to other studies where LiDAR-derived heights are compared to field-measured heights [36]. It is also notable that the 99th percentile, which is sometimes used as a predictor of maximum or dominant height [29], [15], was stable between all four flight lines (Table 3). Overstorey cover varied by an average of 4%. This amount is similar to that reported by [15], who tested the effects of changes in platform altitude on cover estimates. The variation in overstorey cover may simply be inherent to the metric, or it may be related to the large differences in point densities between the four flight lines. For example, [33] demonstrated that changes in point densities affected first return cover estimates; however, they achieved the variation in sampling density by varying PRF from 33 kHz to 70 kHz, confounding our ability to determine the cause of the discrepancy within the context of this study. In this study, the plot-level differences in return numbers observed between flight lines may have been caused by unintended variations in platform orientation and altitude. Although flight parameters were specified with the expectation that they would be held constant, the ability of a pilot to maintain these would depend on skill, aircraft stability, and flying conditions, and pulse densities would vary with deviations from the profile. Finally, the selection of a different plot size can also influence the stability of the precision of LiDAR-derived results, with larger field plots having been shown to aid in compensation for lower pulse densities [19]; a situation also described in the forestry literature, independent of LiDAR perspectives [37].

The intensity of a pulse return is the ratio of received to transmitted energy and is influenced by a variety of factors, including range to target, incidence angle, bidirectional reflectance distribution function, atmospheric transmittance and attenuation, transmitted power, and beam divergence [18]. In their examination of interpolated intensity values, [38] report visible differences between adjacent flight lines and attributed the differences to a lack of calibration between lines. The results presented here indicate that intensity values were strongly and significantly different between flight lines. The reasons behind this variation, particularly the sudden drop in flight line 3, are unknown and highlight the need for documentation of in-flight system settings and post-flight calibration [16], [39].

Our results indicate that metrics derived from last return data are less reproducible than those based on first returns. For example, average variation in last return height percentiles was two to three times that of those derived from first returns (Table 3). The comparative instability in last return data has been reported elsewhere [15], [20], but the results of this study indicate that even when flight and sensor parameters are maintained constant, last return metrics are less reproducible than estimates based on first returns. This highlights the need to treat return categories separately when testing survey parameterizations, and may bring into question the results of studies where this is not done. Furthermore, when developing models between field and laser data, the importance of analyzing different return categories alone and in combination must be emphasized.

Although this study demonstrates the reproducibility of many LiDAR metrics, it must be recognized that within the context of a long term monitoring scenario, repeated surveys will likely be undertaken with different sensors, settings, and flight specifications. Although much previous work has attempted to quantify the effects of these changes, the LiDAR user community has only a limited understanding of many of the fundamental causes, as there is a paucity of publicly available information related to both internal sensor settings, and the relationship between an emitted pulse and detected energy.

Conclusions

The goal of this study was to investigate the reproducibility of plot-based LiDAR-derived vegetation metrics when LiDAR data collection specifications and forest dynamics (e.g. growth or mortality) are not factors. Four overlapping airborne scanning surveys were flown on the same day and plot level comparisons were then performed. Results indicate that few of the first return vegetation measures differed significantly between flight lines, even though resultant hit densities varied between plots extracted from the different flight lines. It is also worth noting that intensity values, largely relating to the magnitude of reflected energy for a given return, varied significantly between the four flight lines. Assuming no real-time adjustments to the actual sensor configuration, this variability suggests that intensity values should be used with caution and only following calibration. Most last return metrics differed significantly and were less robust than those derived from first returns. The observed stability of the height-related vegetation metrics, particularly those based on first return data, should provide confidence to those interested in employing scanning LiDAR as a tool for the accurate characterization of forest environments.

Acknowledgments

Joanne White (Canadian Forest Service), is thanked for aiding with the design and implementation of the LiDAR survey. Generous funding support from the Canadian Forest Service Innovative Ideas program aided in making this research possible.

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Tables

Table 1. LiDAR sensor and flight specifications.

Sensor and Survey Parameters	Value
Sensor Type	TRSI Mark II discrete return sensor
Number of Returns	Two, first and last
Beam Divergence Angle (mrad)	0.5
Wavelength (nm)	1064
Mean Flying Height Above Ground (m)	800
Pulse Frequency (kHz)	50
Mirror Scan Rate (Hz)	30
Scan Angle (degrees)	±15
Mean Footprint Diameter (m)	0.4
Across-track first return posting distance at nadir (m)	0.5
Along-track first return posting distance at nadir (m)	0.5

Table 2. Plot-level summaries of all returns and first returns for each flight line (n = 46 plots).

Variable	Acquisition			
	Flight line 1	**Flight line 2**	**Flight line 3**	**Flight line 4**
Mean number of all returns	2327	3345	2944	4309
Maximum number of all returns	3959	6516	4812	9815
Mean number of first returns	1905	2697	2569	3714
Maximum number of first returns	3432	5623	3928	8651
Mean proportion of first returns (%)	82	81	87	86

Table 3. Results of the multivariate repeated measures ANOVA. Wilk's lambda is a multivariate measure of association, which is then transformed into an *F*-ratio. *p* is the significance of the *F*-ratio. Those variables that were significantly different between flight lines are highlighted in bold ($\alpha = 0.05$, n = 46 plots, effect degrees of freedom = 3, error degrees of freedom = 43).

	Variable	Wilks test value	*F*	*p*	Plot-level grand mean	Absolute mean difference between scan lines
Number of returns	**First and last returns**	**0.33**	**28.99**	**0.00**	**3231**	**1340**
	First returns	**0.29**	**39.00**	**0.00**	**2721**	**1126**
	First returns > 1 m	**0.32**	**30.62**	**0.00**	**2197**	**897**
	Last returns > 1 m	**0.57**	**10.90**	**0.00**	**300**	**179**
Terrain height	Mean height (m)	0.84	2.63	0.06	166.78	0.10
	Standard deviation of height (m)	0.90	1.56	0.21	1.28	0.04
First return vegetation height metrics	Mean height (m)	0.90	1.58	0.21	19.69	0.49
	Standard deviation of height (m)	0.88	2.04	0.12	6.68	0.26
	Maximum height (m)	**0.82**	**3.11**	**0.04**	**33.29**	**0.49**
	Coefficient of variation	0.86	2.30	0.09	36.75	1.97
	Kurtosis	0.92	1.24	0.31	0.51	0.30
	Skewness	0.95	0.82	0.49	-0.60	0.12
	10^{th} percentile (m)	0.90	1.60	0.20	10.61	0.79
	25^{th} percentile (m)	0.87	2.07	0.12	15.28	0.58
	50^{th} percentile (m)	0.91	1.33	0.28	20.54	0.64
	75^{th} percentile (m)	0.96	0.611	0.61	24.66	0.36
	90^{th} percentile (m)	0.98	0.30	0.83	27.60	0.38
	95^{th} percentile (m)	0.98	0.35	0.79	29.15	0.42
	99^{th} percentile (m)	0.95	0.70	0.56	31.45	0.41
Cover metrics	Understorey cover (%)	0.86	2.40	0.08	4.06	0.84
	Overstorey cover (%)	**0.77**	**4.27**	**0.01**	**80.32**	**2.60**
Last return vegetation height metrics	**Mean height (m)**	**0.58**	**10.27**	**0.00**	**15.27**	**1.26**
	Standard deviation of height (m)	0.99	0.16	0.93	6.77	0.43
	Maximum height (m)	**0.61**	**8.98**	**0.00**	**28.89**	**1.38**
	Coefficient of variation	**0.64**	**7.96**	**0.00**	**46.54**	**4.46**
	Kurtosis	**0.72**	**5.55**	**0.00**	**-0.47**	**0.36**
	Skewness	**0.79**	**3.72**	**0.02**	**-0.19**	**0.19**
	25^{th} percentile (m)	**0.63**	**8.25**	**0.00**	**10.36**	**1.51**
	50^{th} percentile (m)	**0.70**	**6.28**	**0.00**	**15.82**	**1.57**
	75^{th} percentile (m)	**0.68**	**6.72**	**0.00**	**20.38**	**1.26**
	95^{th} percentile (m)	**0.79**	**3.72**	**0.02**	**25.41**	**1.24**
Intensity	**Mean of first returns**	**0.188**	**61.78**	**0.00**	**1771**	**278**
	Standard deviation of first returns	**0.119**	**106.4**	**0.00**	**819**	**249**
	Mean of last returns	**0.25**	**42.26**	**0.00**	**598**	**143**
	Standard deviation of last returns	**0.21**	**55.29**	**0.00**	**720**	**168**

Absolute scan angle	Mean (degrees)	0.96	0.60	0.62	5.14	3.37
	Standard deviation (degrees)	0.92	1.22	0.32	0.95	0.11

Figures

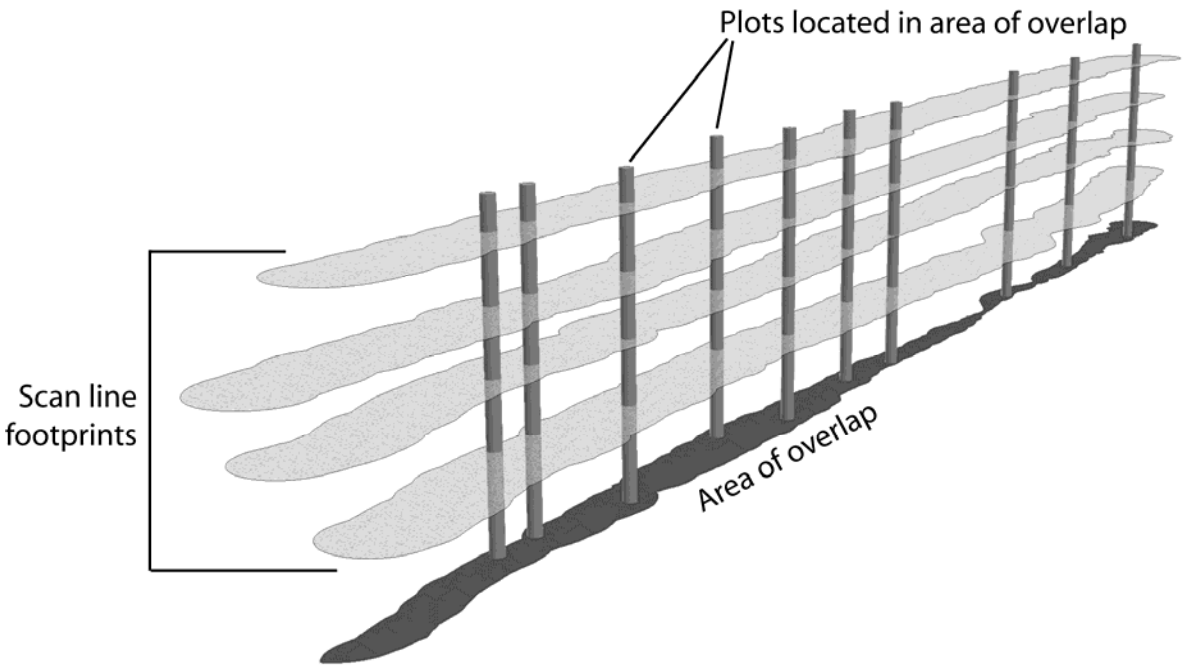

Fig. 1. Conceptual design of the repeat pass LiDAR survey. Four flight lines were flown along a 3-km-long forested transect, and then plot-level vegetation metrics were extracted from each from within the area of overlap for comparison. (Note that objects are not to scale.)

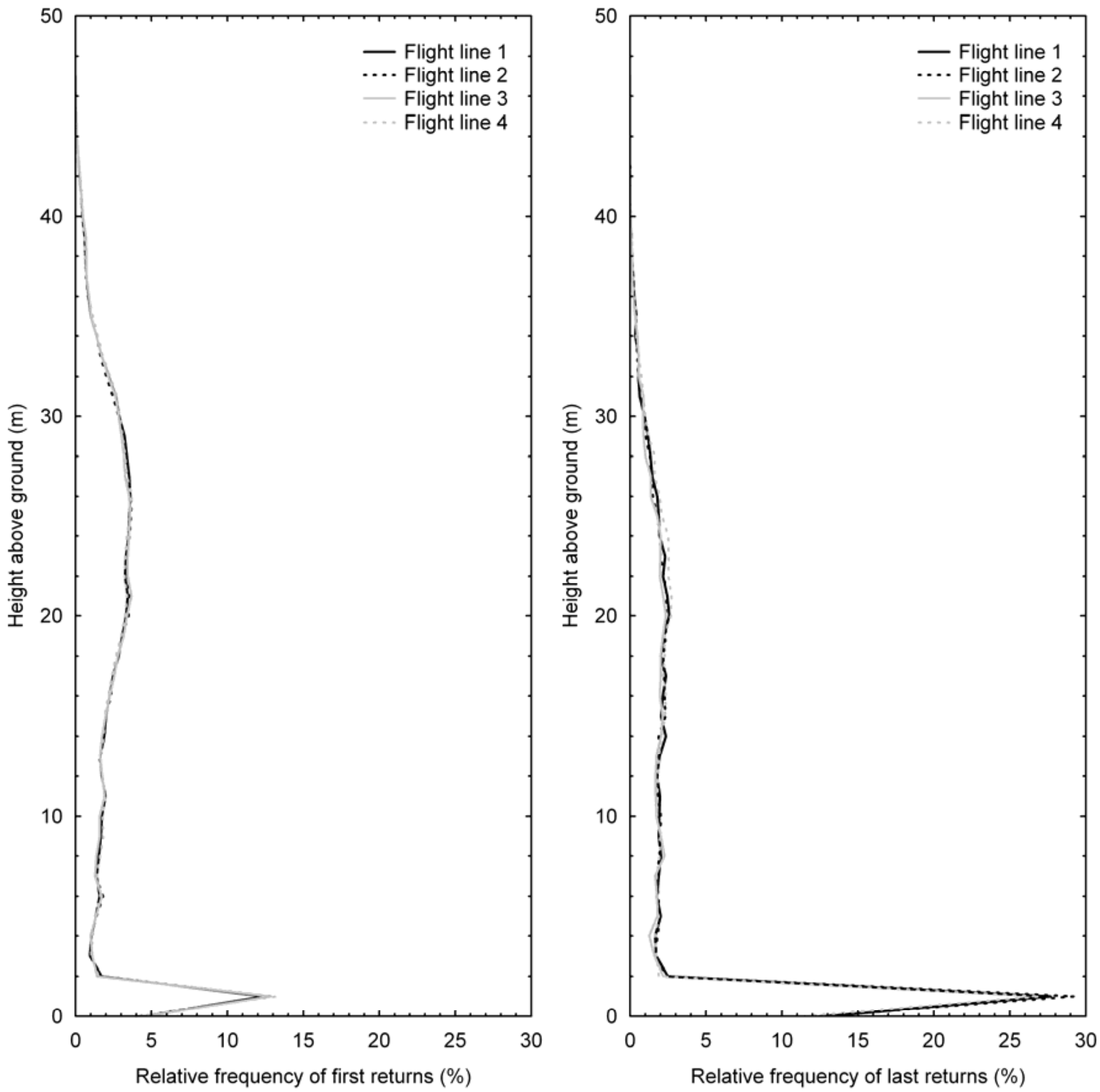

Fig. 2. Aggregated vertical distributions of first and last returns extracted from forty-six 0.04 ha plots within the four flight lines.

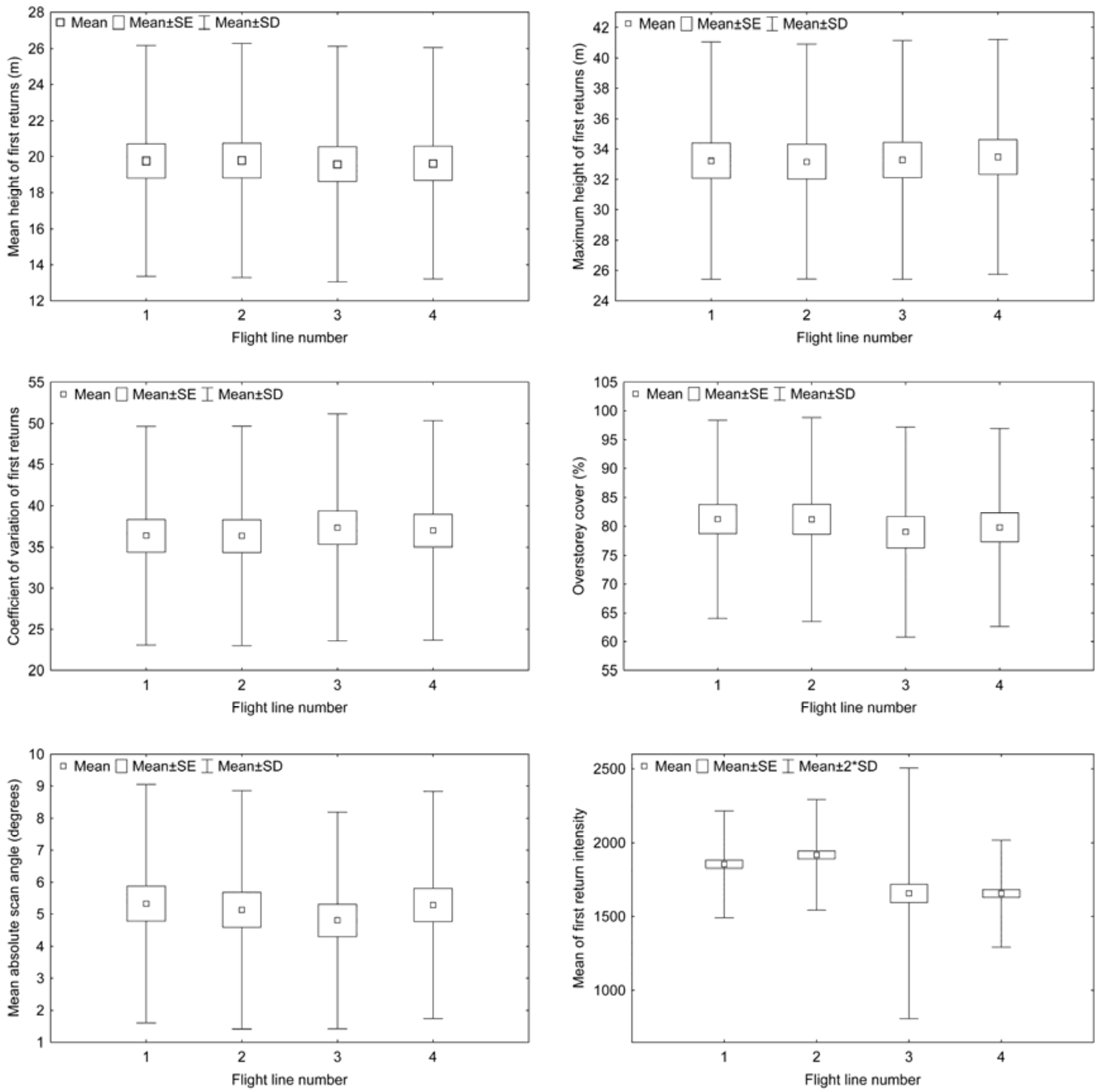

Fig. 3. Plot-level means, standard errors, and standard deviations for selected first return vegetation metrics and absolute scan angles grouped by flight line (n = 46 plots).