ESTIMATION OF ABOVEGROUND FOREST BIOMASS USING AIRBORNE SCANNING DISCRETE RETURN LIDAR IN DOUGLAS-FIR

K. S. Lim* and P. M. Treitz

Department of Geography, Faculty of Arts and Science, Queen's University, Kingston, Ontario, K7L 3N6, Canada -
9KK14@qlink.queensu.ca, treitzp@post.queensu.ca

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ABSTRACT:

Models based on laser height metrics matching different quantiles of the distribution of laser canopy heights should be similar to one another with respect to their predictive capabilities of aboveground biomass providing: 1) the allometric relationships in the trees studied remain consistent; and 2) the vertical distributions of laser canopy heights and needle area/mass are related according to a simple quantile-quantile relationship. To explore the use of canopy-based quantile estimators in an application of aboveground biomass estimation in Douglas-fir, models based on laser height metrics corresponding to deciles of the distribution of laser canopy heights are compared. Because robust allometric equations were not available, the influence of using two different sets of allometric equations (referred to as BAR and TER equations) on model results is examined. The coefficient of determination (r^2) of decile models in the BAR and TER groups ranged from 0.25 to 0.43 and 0.34 to 0.50, respectively, whereas the root-mean-square error (RMSE) ranged from 29 to 34 and 32 to 36 Mg/ha, respectively. The greatest difference in RMSE between models was less than 5 Mg/ha. Decile models for each of the BAR and TER groups were not overtly different from one another.

1. RATIONALE FOR STUDY

Our previous research in sugar maple (*Acer saccharum* Marsh.) in central Ontario, Canada demonstrated the potential of several, yet different canopy-based quantile estimators derived from airborne scanning lidar data to estimate aboveground biomass (AB) (Lim *et al.*, *in press*). Models based on different canopy-based quantile estimators were found to be comparable to one another with respect to their predictive capabilities (i.e., coefficient of determination (r^2) and root-mean-square error (RMSE)) (Lim *et al.*, *in press*).

To explore how well canopy-based quantile estimators can be generalized to other forest types for applications of AB estimation and to avoid having to make an assumption of how the vertical distributions of laser returns and needle area are related, models based on canopy-based decile estimators were developed for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in western Canada using the same ground reference and airborne scanning lidar data reported in Magnussen and Boudewyn (1998).

2. MATERIALS AND METHODS

2.1 Study Site

The study site was the Shawnigan Lake (SL) thinning and fertilization trial with Douglas-fir near SL, British Columbia, Canada (Figure 1). The thinning and fertilization trial at the SL site (48.38°N, 123.43°W) was initiated in 1970 to study the effects of thinning and nitrogen fertilization on a 24-year old Douglas-fir stand, which was a fairly homogeneous stand (~50 ha) with a site index of 25 m at age 50 and predominantly composed of planted Douglas-fir trees (Crown and Brett, 1975; Barclay *et al.*, 1986).

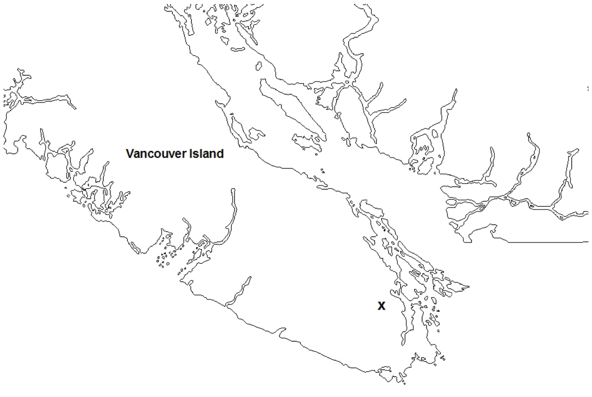

Figure 1. Location of the Shawnigan Lake trial on Vancouver Island, British Columbia, Canada.

A total of nine different treatments, consisting of different combinations of degrees of thinning and levels of fertilization, were applied to the sample plots. The three degrees of thinning varied from no thinning (T_0) to intermediate (T_1) and heavy thinning (T_2). For the T_1 and T_2 thinning, approximately 1/3 and 2/3 of the basal area were removed, respectively. The three different levels of fertilization included no fertilization (F_0), 224 (F_1), and 448 (F_2) kg of nitrogen per ha. Historically, nine years after the initial treatments (i.e., 1981), sample plots that were initially fertilized were re-fertilized using the same dosage, whereas only the F_1 sample plots were re-fertilized 18 years after initial treatments (i.e., 1990).

2.2 Ground Reference Data

Thirty-six sample plots from the SL thinning and fertilization trial were considered. The dimensions of each sample plot were

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* Corresponding author.

20 m x 20 m. Sample plots were georeferenced using differential GPS resulting in a nominal planimetric accuracy of 1 to 2 m (Magnussen and Boudewyn, 1998). The DBH of all trees in each sample plot were measured in the winter of 1995 when the trees were 49-years old. Because the lidar data were acquired in 1996, to synchronize the two data sets, all DBH measurements were prorated by one year using tree- and trait-specific relative growth rates that were estimated for the period between 1995 and 1996 (McWilliams and Therien, 1996; Magnussen and Boudewyn, 1998).

2.3 Allometric Equations

Given the uncertainty surrounding the representativeness of the available site-specific allometric equations of the allometric relationships in the present Douglas-fir, two different sets of allometric equations were used to estimate aboveground biomass from the ground reference data. They included: (1) dated site- and treatment-specific allometric equations (Barclay *et al.*, 1986) (referred to as the BAR equations); and (2) an allometric equation developed by Ter-Mikaelian and Korzukhin (1997) (referred to as the TER equation) for uneven-aged interior Douglas-fir trees in northern British Columbia using data published by Marshall and Wang (1995). In the case of the set of BAR allometric equations, for treatments missing a treatment-specific allometric equation, the allometric equation for the control treatment (i.e., T_0F_0) was substituted.

2.4 Lidar Data

The SL site was surveyed in the second week of December 1996 using an Optech Airborne Laser Terrain Mapper (ALTM) 1020 (Optech Inc., Toronto, Canada). The ALTM 1020 emits laser pulses with a wavelength of 1047 nm and records only the first or last return for any given laser pulse. Two parallel flight lines were flown twice (i.e., back and forth) at an altitude of 600 m above ground level using an aircraft speed of 40 m/s. The first pass of a given flight line was used to record first returns, whereas the second pass of the same flight line was used to record last returns. The footprint of each laser pulse was approximately 30 cm. The pulse repetition frequency varied between flight lines and ranged from 2 to 8 kHz, whereas the scan angle never exceeded 12°.

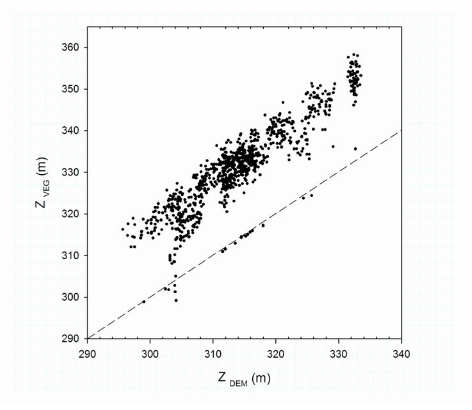

Figure 2. The z-value of laser returns plotted against the z-value on the DEM matching its x-y coordinates (sub-sample of approximately 50% of data).

2.5 Generation of DEM

Using the classified ground laser returns and the inverse distance weighted interpolator (12 nearest neighbours by Euclidean distance; power of 2), a digital elevation model (DEM) with a cell resolution of 1 m was interpolated.

2.6 Extracting Laser Canopy Returns

For each laser return, the z-value is typically referenced to the ellipsoid. When the z-value of each laser return is plotted against the z-value on the DEM matching that laser return's x-y coordinates, misclassified vegetation laser returns, corresponding to those laser returns near the 1:1 line, are observed (Figure 2).

When the spatial distribution of laser returns for each sample plot is plotted in 3-D, it becomes evident that laser returns reflected from the forest canopy can be easily differentiated from those laser returns that were misclassified as vegetation returns (Figure 3). A 'hard' threshold of 3 m was identified as a suitable threshold for removing misclassified vegetation returns.

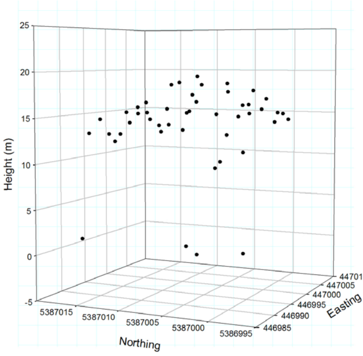

Figure 3. Spatial distribution of laser returns in 3-D illustrating the clear distinction between forest canopy and non-canopy laser returns.

2.7 Canopy-based Quantile Estimators

To derive interpretable measures of vegetation height, the z-values of laser returns must be normalized to the terrain. This process is accomplished by using the interpolated DEM, where the z-value on the DEM matching the x-y values of each laser canopy return is subtracted from that laser return's z-value. Canopy-based quantile estimators are derived for each sample plot and consist of selecting laser height metrics that correspond to deciles of the distribution of laser canopy heights for each sample plot.

2.8 Statistical Model and Inference

A simple linear regression model was the basis of all regression analyses. Preliminary data analysis suggested that the assumptions underlying linear regression were not violated when this type of model was adopted in conjunction with the data and therefore, a data transformation or specification of an alternate model was not required. Models within each allometric equation group were compared to one another based on the r^2 and RMSE of each model.

3. RESULTS

Results from the statistical analyses are summarized in Table 1. For models based on BAR estimates of biomass, the r^2 differed at most by 18% and ranged from 0.25 to 0.43. The r^2 decreased as the decile matched by laser canopy heights for each model increased. The greatest difference between the RMSE of these models was 4.41 Mg/ha, with RMSE values ranging from 29.22 to 33.63 Mg/ha. Similarly, the RMSE increased as the decile matched by laser canopy heights for each model increased. For each model, the linear relationship was significant (all $p <$ 0.002).

Similar results to those obtained for models based on BAR estimates of biomass were found for those models developed using TER estimates of biomass. The same general trend of increasing r^2 and decreasing RMSE with decreasing decile model was observed. The r^2 of each decile model based on TER estimates of biomass ranged from 0.34 to 0.50 resulting in a difference of 16%. The RMSE of TER decile models ranged from 31.52 to 36.35 Mg/ha. The greatest difference between the RMSE of each TER decile model is 4.83 Mg/ha. For each TER decile model, the linear relationship was significant (all $p <$ 0.0002).

The r^2 of each decile model based on TER estimates of biomass was consistently greater than those found for corresponding decile models based on BAR estimates of biomass. The 16% difference between the lowest and highest r^2 for the TER models is 2% less than the maximum difference found for BAR decile models. The greatest difference of 4.83 Mg/ha between the RMSE of each TER decile model is only slightly greater than the difference of 4.41 Mg/ha found for the BAR decile models. Comparing the RMSE for each matching BAR and TER decile model reveals that the RMSE of the TER decile models are consistently greater than those found for the BAR models, with the greatest difference of 2.81 Mg found between the BAR and TER 90th percentile models. Although the r^2 of TER decile models are slightly higher than those found for the BAR decile models, the trade-off is a small increase in RMSE for the TER decile models.

4. DISCUSSION

The allometric relationships in the Douglas-fir considered in this study may be inadequately represented by either the BAR and TER allometric equations. Mitchell *et al.* (1996), who studied the effects of thinning and fertilization on biomass and nutrient element dynamics in Douglas-fir in the SL trial, reported that 18 years after initial treatments, total aboveground biomass varied between treatments. The total aboveground biomass in the T_0F_0, T_0F_2, T_2F_0, and T_2F_2 treatments were 243, 231, 138, and 206 Mg/ha, respectively. Although the percent of total biomass allocated to foliage biomass varied only slightly between the four treatments considered (i.e., 3.8 to 5.8 %), Mitchell *et al.* (1996) reported that the aboveground biomass in other tree components (e.g., live branch) was significantly affected by thinning and fertilization, implying variable allometric relationships in the Douglas-fir.

While canopy-based quantile estimators may estimate needle mass in Douglas-fir, if the allometric relationships between the remaining tree components are variable, then the inconsistent allometric relationships can account for the observed variability around the regression line for both groups of models. Moreover, the substitution of the T_0F_0 equation for treatments with no specific allometric equation likely introduced additional sources of error. The results from Mitchell *et al.* (1996) and a similar study carried out earlier by Barclay *et al.* (1986) reporting similar conclusions, justifies and confirms the initial concerns over the representativeness of the BAR and TER allometric equations of the allometric relationships in the Douglas-fir at SL.

5. CONCLUSION

The results of this study in Douglas-fir complements previous research by Lim and Treitz (*in press*) in sugar maple and demonstrates the potential of canopy-based quantile estimators derived from lidar data in applications of aboveground biomass estimation. Furthermore, these results suggest that canopy-based quantile estimators can be generalized to other tree species and forest types. The r^2 of all models developed in this study ranged from 0.25 to 0.50, whereas the RMSE of models in the BAR and TER groups did not vary considerably, with the greatest difference between any two models in each group less than 5 Mg/ha. Therefore, in terms of model performance, all deciles model within each of the BAR and TER groups were comparable with no overt differences. Errors associated with the decile models can be potentially attributed to the use of imprecise allometric equations for estimating aboveground biomass from the ground reference data. Robust allometric equations are essential to empirical studies of this nature.

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Allometric Equation	Decile Model	β_0 (intercept)			β_1 (slope)			r^2	RSE	RMSE (Mg/ha)
		Value	Std. Error	*p*-value	Value	Std. Error	*p*-value			
BAR	1st	92.32	27.44	0.002	9.27	1.81	< 0.001	0.435	30.07	29.22
	2nd	79.87	30.39	0.013	9.48	1.89	< 0.001	0.426	30.31	29.45
	3rd	85.49	32.82	0.014	8.73	1.95	< 0.001	0.370	31.74	30.84
	4th	84.81	35.23	0.022	8.48	2.03	< 0.001	0.340	32.51	31.59
	5th	84.03	37.24	0.031	8.26	2.08	< 0.001	0.317	33.06	32.12
	6th	84.10	37.23	0.030	7.99	2.01	< 0.001	0.317	33.06	32.13
	7th	84.22	38.48	0.036	7.77	2.03	< 0.001	0.302	33.41	32.47
	8th	83.65	40.96	0.049	7.50	2.07	0.001	0.278	33.99	33.04
	9th	81.33	44.45	0.076	7.28	2.15	0.002	0.252	34.60	33.63
TER	1st	99.76	29.60	0.002	11.47	1.95	< 0.001	0.503	32.43	31.52
	2nd	81.30	32.33	0.017	11.93	2.01	< 0.001	0.509	32.25	31.34
	3rd	83.69	34.78	0.022	11.26	2.07	< 0.001	0.466	33.63	32.69
	4th	80.53	37.41	0.039	11.07	2.15	< 0.001	0.437	34.51	33.54
	5th	78.60	39.74	0.056	10.83	2.22	< 0.001	0.412	35.28	34.28
	6th	78.59	39.72	0.056	10.49	2.15	< 0.001	0.413	35.27	34.27
	7th	77.87	41.15	0.067	10.25	2.17	< 0.001	0.397	35.73	34.72
	8th	76.16	44.06	0.093	9.94	2.23	0.0001	0.369	36.56	35.53
	9th	71.54	48.05	0.146	9.73	2.34	0.0002	0.339	37.41	36.35

Table 1. Results from regressing estimates of biomass derived from the BAR and TER equations against canopy-based quantile estimators.