Estimating single-tree branch biomass of Norway spruce by airborne laser scanning

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Abstract
Dry weight of the branches of 20 trees of Norway spruce was obtained through destructive sampling. Airborne laser scanning data from the same trees were used to calculate crown volume for each tree. The crown volume was derived by using the crown laser echoes with a radial basis function to construct a crown surface. A regression model was fitted to the data, with the crown volume as explanatory variable and the dry weight of the branches as response. The model revealed a strong relationship between the two, with $R^2 = 0.80$. A leave-one-out cross-validation gave a root mean square error of 34%.

Keywords: Airborne laser scanning, biomass, crown volume, bioenergy

1. Introduction
The last ten years has seen an increased interest in the use of biomass for energy purposes. Biomass from forests will most likely be one of several sources of energy that will replace fossil fuels in the future. One obvious example is the utilization of logging residues, biomass that would otherwise have been left in the forest during the logging. The branch biomass constitutes a considerable part of the logging residues. When logging residues become a commercial product from the forest, this resource should be quantified as part of the forest inventory to improve planning of extraction for energy purposes. An increasing part of forest inventories are based on data collected with airborne laser scanning (ALS). While many ALS based operational forest inventories are using the area-based approach as described by e.g. Næsset (2002), also methods targeting single trees have been proposed (Hyyppä et al. 2001; Persson et al. 2002; S. Solberg et al. 2006; Wang et al. 2008). The latter methods usually require ALS data with higher resolution, but intend to give information on a single tree level, contrary to the per area information provided by the former. Although not as widely used at the moment, inventory methods targeting individual trees might in the future be more used, depending on the ongoing technological and methodological research and development and future costs for data acquisition. The potential of estimating individual tree characteristics by ALS has been investigated in several studies, including stem volume (Straub & Koch 2011), stem diameter (Popescu 2007), crown base height (Vauhkonen 2010), leaf area index (Roberts et al. 2005) and biomass (Popescu 2007).
When a tree is scanned by an airborne laser scanner, a majority of the laser pulses will echo from the crown, i.e. the branches. This suggests that the ALS data contain useful information on the crown biomass. In fact, much of the information inherent in the ALS data will be directly related to the tree crown and the branches. In a previous study on single-tree biomass estimation from ALS (Popescu 2007) a strong relationship between the ALS data and the branch biomass was reported. The actual branch biomass of each individual tree was however not measured, but obtained through allometric equations with field measured tree height \( h \) and diameter at breast height \( d_{bh} \) as explanatory variables. A direct relationship between ALS data and branch biomass were therefore not established.

Single-tree predictor variables derived from the ALS point cloud such as height percentiles and crown diameter have been used by e.g. Popescu et al. (2003) and Straub & Koch (2011). Kato et al. (2009) presents a method for crown surface reconstruction that enables the calculation of crown volume. An intuitive assumption is that this crown volume could be a good predictor variable for estimation of branch biomass.

To our knowledge no previous studies relates ALS data directly to accurate measurements of branch biomass (i.e. obtained with destructive sampling) at a single tree level. The first aim of the present study was therefore to assess the accuracy of ALS based predictive models for single-tree branch biomass of Norway spruce \( \text{(Picea abies (L.) Karst.)} \) using ground measurements of branch biomass. The second aim was to assess the suitability of using an ALS derived crown volume as a predictor variable for branch biomass. This variable was chosen based on the above mentioned assumption, and promising results from a pre-study comparison of some ALS derived variables (not included in the present study).

2. Materials and methods

2.1 Study area
The study area was Aurskog-Høland municipality \( (59°50' N 11°30' E, 120-390 \text{ m above sea level}) \) located in the south-eastern part of Norway. The total area of Aurskog-Høland is 96,000 ha with 67,000 ha productive forest. The forest type is boreal with Norway spruce \( \text{(Picea abies (L.) Karst.)} \) as the dominant tree species.

2.2 Field data
Field data were collected in June 2009. Two locations were chosen, and from each location 10 trees were selected. The two locations were chosen from potential locations in the intersections of the two east-west strips of already existing ALS data (see section 2.3) and forest roads. In order to avoid edge effects from the forest roads, trees with a distance >10 m to the forest road were preferred. Finally, due to practical reasons, trees with a distance >30 m from the road were not selected.

On all the 20 selected trees the crown projection was measured in the eight cardinal and intercardinal directions. The measurements were carried out with a measuring tape and a compass. The horizontal distance from the stem at breast height to the vertical projection of the branch tip in the given direction was recorded. For all trees \( d_{bh} \) was measured with a calliper.

The 20 trees were then felled, and the raw weight of the branches (including needles) of each tree was obtained by weighing the tree before and after the branches were cut off. The weighing was done with a mobile lift mounted on a truck. A Teraoka Seiko OCS-XZL digital scale with load capacity 3000 kg
was used. Samples of entire branches were selected among the living branches of each tree in order to determine the dry weight. In total 11 living branches were taken from each tree, i.e., three branches from the lower part of the crown, three from the middle part and three from the upper part of the crown. In addition two branches were taken from the top of the stem ($d_{bh} < 5$ cm). From all the sampled branches there were taken three sub-samples which were dried and the raw and dry weight of each sub-sample was recorded. For each tree $h$ was measured with a measuring tape after the felling.

The coordinates of each tree were obtained in a two-step procedure: (1) The location of each tree relative to two local reference points was accurately measured with a total station, and (2) the coordinates of the two reference points were obtained by differential Global Navigation Satellite Systems (dGNSS), using dual-frequency receivers observing pseudo-range and carrier phase of the Global Positioning System and the Russian Global Navigation Satellite System. Hasegawa & Yoshimura (2003) found horizontal positional errors in the range of 1 – 30 cm in dGNSS-measurements under conditions comparable to those in the present study.

Characteristics of the 20 trees are summarized in Table 1.

Table 1: Summarized characteristics of the 20 trees in the data material. Field measured $d_{bh}$, $h$ and dry weight of the branches ($BR_{dw}$).

<table>
<thead>
<tr>
<th></th>
<th>$d_{bh}$ (cm)</th>
<th>$h$ (m)</th>
<th>$BR_{dw}$ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>11.2</td>
<td>8.2</td>
<td>8</td>
</tr>
<tr>
<td>max</td>
<td>39.8</td>
<td>26.3</td>
<td>156</td>
</tr>
<tr>
<td>mean</td>
<td>23.6</td>
<td>19.6</td>
<td>69</td>
</tr>
</tbody>
</table>

2.3 ALS data

ALS data were collected along two strips in east-west direction in the study area. The strips were flown 9 km apart in the north-south direction.

The dataset was collected in June 2006 with an Optech ALTM 3100 sensor on a fixed-wing aircraft. The average flying altitude was 800 meter above ground, the pulse repetition frequency was 100 kHz, the scan frequency 70 Hz and the maximum scan angle was ±5 degrees from nadir. This gave an average point density on the ground of 7-10 m$^2$.

Classification of echoes into ground- and vegetation echoes was carried out by the contractor with the TerraScan software (Anon. 2011). The contractor also determined the planimetric coordinates and ellipsoidal height values for all echoes. Echoes classified as ground were used to construct a triangulated irregular network (TIN) terrain model. The height above ground was calculated for all echoes by subtracting the respective TIN heights from the ellipsoidal heights.

First and last recorded echoes were used in the present study.

2.3.1 Single tree segmentation

Several methods for automatic delineation of the ALS point cloud into single tree segments have been proposed. However, automatic segmentation will always omit some trees (omission errors) and include false trees (commission errors) (Vauhkonen et al. 2011). To avoid errors introduced by automatic segmentation, we decided to use the field measured crown projection for selection of echoes
that could be assigned to each individual tree. An eight-sided polygon was formed from the crown projection measurements of each tree, and all echoes within the polygon were assigned to that tree.

2.4 Calculations

2.4.1 Dry weight biomass of the branches
A raw to dry weight ratio was calculated for each branch sub-sample. For each tree a raw to dry weight ratio was calculated as the mean of the ratios obtained from the samples. Finally, the total dry weight biomass of the branches for each tree was calculated as the raw weight of the branches multiplied with the calculated tree-specific raw to dry weight ratio. This is denoted $BR_{dw}$ in the rest of this paper.

2.4.2 ALS derived crown base height
The crown base height was estimated from the height of the laser echoes in each tree. A simple procedure was applied, where only the echoes below the median height were considered. These echoes were sorted according to their height above ground, and the echo with the largest vertical distance to the next echo below was set to be the lowermost echo in the crown, and hence the crown base height (Fig. 1). Laser echoes above the crown base height were considered to be crown echoes.

![Figure 1: Estimated crown base height for four of the trees in the data material.](image-url)

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1 Contrary to definitions of crown base height used by e.g. Maltamo et al. (2010) where the base height refers to the height on the tree trunk where the lowermost branches are found, we wanted in this study the crown base height to correspond to the height of the lowermost point on any of the branches in the live crown.
2.4.3 Radial Basis Function derived crown volume

Crown volume was calculated from the crown echoes for each tree by using a radial basis function (RBF) as proposed by Kato et al. (2009). The method was modified to work with less dense ALS data, and the calculations can briefly be summarized as follows:

Points on the surface of the crown to be reconstructed were chosen by calculating a convex hull in the x,y-plane for the echoes in a number of individual height bins. The echoes at the border of the convex hull were marked as surface points, all others as being inside the crown. The topmost and lowermost echoes in the point cloud were always marked as being on the crown surface.

For each surface point two off-surface points were created (see Carr et al. (2001) for details) in a given distance \( d \) from the surface point. An RBF can in this case be written as

\[
f(x) = \sum_{i=1}^{N} \lambda_i(|x - x_i|),
\]

where \( x \) is a point \( \in \mathbb{R}^3 \), \( N \) is the number of all the surface and off-surface points and \( |x-x_i| \) is the Euclidian distance. The \( \lambda_i \) is a weight parameter, computed with the distance values \( d \) and the surface and off-surface points. When the \( \lambda_i \)s are determined the RBF in Equation 1 can be evaluated for any given point \( x \in \mathbb{R}^3 \). and it has the property that \( f(x) \) will be zero at the crown surface. A crown surface was approximated by evaluating Equation 1 for values of \( x \) in a three-dimensional grid, and constructing a triangulated mesh surface where \( f(x) = 0 \) (visualized in Fig. 2). The crown volume \( V_{cr} \) for each tree was then calculated from the triangulated mesh crown surface by

\[
V_{cr} = \sum_{i=1}^{M} V(t_i),
\]

where \( M \) is the number of triangles in the mesh, \( V \) is a signed volume function and \( t_i \) is the tetrahedron formed by the \( i \)th triangle and an arbitrary point \( p \). The facing of the \( i \)th triangle relative to \( p \), determines the sign of \( V \).
2.4.4 Model fitting and validation
A linear regression model with $V_c$ as explanatory variable and $BR_{dw}$ as response variable was fitted to the data. A leave-one-out cross-validation was carried out by leaving out one observation at the time, re-fitting the model with the remaining trees and predicting the biomass for the single tree left out.

2.4.5 Biomass by existing allometric equations
For comparison reasons the biomass of the branches for the 20 trees were also estimated by existing allometric equations with field measured $d_{bh}$ and $h$ as explanatory variables (Marklund 1988).

3. Results
The Pearson’s correlation coefficient between the biomass of the branches and the ALS derived crown volume was 0.892, which means that the ALS crown volume explained approximately 80% of the variation in branch biomass in the regression model (Table 2). The leave-one-out cross-validation gave a root mean square error (RMSE) of 34%.

When relating the $BR_{dw}$ to the branch biomass estimated with existing allometric equations with field measured $d_{bh}$ and $h$ as explanatory variables the correlation coefficient was 0.866. The RMSE for these estimates was 31%. Plots of the residuals (Fig. 3) show that the accuracy of the field based estimates from the existing allometric equations is slightly better than the accuracy obtained in the cross-validation of the ALS based regression model.
Table 2: Estimated regression model and associated statistics. RMSE from cross-validation of the model.

<table>
<thead>
<tr>
<th>Response variable</th>
<th>n</th>
<th>Predictive model</th>
<th>$R^2$</th>
<th>Observed mean (kg)</th>
<th>RMSE (kg)</th>
<th>RMSE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BR_{db}$</td>
<td>20</td>
<td>$14.765 + 0.562 \cdot V_{cr}$</td>
<td>0.80</td>
<td>69</td>
<td>23</td>
<td>34</td>
</tr>
</tbody>
</table>

Figure 3: Plots of the residuals from the regression model cross-validation and from the branch biomass estimates based on existing allometric equations. The residuals in the left plot are plotted in increasing order by tree size ($dbh$).

4. Discussion and conclusions

A strong relationship was found between the ALS data and the biomass of the branches. The accuracy of the ALS based model predictions is almost comparable to the accuracy obtained with allometric equations based on field measurements. This biomass estimate, derived with the existing allometric equation, is in fact equal to a theoretical ‘best case’ biomass estimate following the procedure described by Popescu (2007), assuming that $dbh$ and $h$ can be perfectly derived from the ALS data. In a real situation this will not be the case, and errors introduced when predicting $dbh$ and $h$ from ALS data will directly affect the biomass estimates derived this way. With this in mind the comparison suggests that, in practice, a comparable accuracy can be obtained by predicting the branch biomass directly from the ALS data, without using a model chain with an independent allometric equation. The main challenge with such an approach is however the dependency on field measurements as training data. Destructive sampling is obviously not an option in an operational setting, so other methods to estimate the ground truth values of branch biomass should be explored. Terrestrial laser scanning has emerged as a possible tool for this purpose, but more research is needed on this issue.

Only one ALS derived variable was considered in this study, and including other ALS derived predictor variables will most likely improve the results. The properties of the RBF crown volume could be explored, and also how these are related to ALS point density, scanning angle and echo
return categories. Since the RBF crown volume is highly dependent on the estimated crown base height, more robust methods to estimate the crown base height might improve the results.

In conclusion, the present study revealed a strong relationship between ALS data and accurately measured branch biomass of Norway spruce at a single tree level. Furthermore, the ALS derived variable describing crown volume was shown to be a promising candidate when predicting branch biomass.

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