Comparison of individual tree detection and canopy height distribution approaches: a case study in Finland

Petteri Packalén[1], Juho Pitkänen[2] & Matti Maltamo[1]
[1] Faculty of Forest Sciences, University of Joensuu, P.O. Box 111, FIN-80101 Joensuu, Finland, Petteri.Packalen@joensuu.fi, Matti.Maltamo@joensuu.fi
[2] Finnish Forest Research Institute, Joensuu Research Unit, P.O. Box 68, FI-80101 Joensuu, Finland, Juho.Pitkanen@metla.fi

Abstract

The two main approaches in ALS based prediction of growing stock characteristics of forests have been individual tree detection (ITD) and canopy height distribution based modelling (CHD). There are numerous studies, in which either of these approaches have been used with a particular test area and dataset. However, the results obtained are not directly comparable between different datasets and areas. In this paper we present a comparison of ITD and CHD using the same validation dataset. The validation data consisted of 41 sample plots, located in a boreal managed forest. ITD and CHD produced equally accurate estimates with respect to stem volume and Lorey's height. The RMSE was about 22% for volume and about 8% for Lorey's height. The residuals were also similar with both methods. Stem number estimates were less accurate with both approaches; particularly ITD had a large RMSE and bias in the form of underestimation. This study indicated that, when considering total stem volume, both ITD and CHD are potential inventory approaches in managed boreal forests. CHD has a cost benefit in the acquisition of ALS data but, on the other hand, it requires more field work in the collection of modelling data.

Keywords: individual tree detection, canopy height distribution

1. Introduction

The two main approaches for predicting growing stock characteristics of forests using ALS data are the canopy height distribution approach (CHD), usually used with low-resolution data (e.g. Næsset 2002; Lim et al. 2003; van Aardt et al. 2006; Maltamo et al. 2006), and the individual tree detection approach (ITD), used with high-resolution data (e.g. Hyyppä and Inkinen 1999; Persson et al. 2002; Popescu et al. 2003; Peuhkurinen et al. 2007). Low resolution means in this context that the pulse density at ground level is about one per square metre and high resolution means about 5-10 pulses per square metre. Most studies have concentrated on predicting characteristics of forest stands or trees as a whole, but characteristics by tree species have also been considered using both approaches (e.g. Holmgren and Persson 2004; Packalén and Maltamo 2007; Holmgren et al. 2008).

The major difference between the laser canopy height distribution and the individual tree based approach is that the latter relies on the detection of individual trees and allometric relationships at tree level, whereas the former uses height hits directly at the plot, microstand or stand level to estimate growing stock characteristics. A common method in individual tree delineation is to detect trees from an interpolated canopy height model by locating local maxima of the height values. After that trees are segmented around local maxima by some region growing algorithm, for instance. In the canopy height distribution approach regression modelling is the most often used estimation technique, although other techniques, such as non-parametric estimation, have also been utilized. Most actual forestry applications have so far been based on the canopy height distribution approach.

There are numerous studies regarding either of the two approaches in which the accuracy of some inventory attributes have been reported using a particular test area and dataset. This naturally raises the question which approach produces more accurate estimates for forest characteristics. However, obtained accuracies are not directly comparable between different datasets and areas. In this paper we present a comparison of ITD and CHD using the same validation dataset. Estimates are compared at the plot level and emphasis is given to the objectivity of the comparison. The aim is to compare the accuracy of ITD and CHD and to examine similarities and differences of the estimates.

2. Method

2.1 Study area and field data

The area concerned is a typical boreal managed forest area in eastern Finland, and hence it is dominated by coniferous tree species. A network of 472 circular sample plots with a radius of 9 metres was measured during the summer in 2004. Sample plots were distributed over 67 forest stands. Differential GPS was used to determine the position of the centre of each plot to an accuracy of approximately 1 m. The diameter at breast height (dbh), tree and storey class, and tree species were measured for each tree with a dbh greater than 5 cm. Height was measured for one sample tree of each species and storey class by plots. This data was required for calibration of the tree species-specific height models of Veltheim (1987), which were used to calculate the heights of the rest of the trees. The volumes of individual trees were calculated as a function of dbh and tree height using the models of Laasasenaho (1982) and summed at the plot level. Lorey's mean height was calculated for each plot by multiplying the tree height by its basal area and then dividing the sum of this calculation by the total basal area of a plot.

A subset of 41 of the sample plots described above were selected to be used as test data in this study (Table 1). These sample plots were the ones located in the area from which both high and low resolution ALS data were available and the dominant tree species in the selected plots was either Scots pine (*Pinus Sylvestris L.*) or Norway spruce (*Picea abies (L.) Karst.*). Another subset of 56 sample plots was used as modelling data in CHD (Table 1). First all the stands which contained test plots were excluded and then one sample plot was chosen randomly from each stand left to be included in the modelling data. Thus, the test data was not used in modelling.

Table 1: Main characteristics of the growing stock in the sample plots of the test and modelling datasets.

	n	min	max	mean	std
CHD Modelling data	56				
Volume, m^3ha^{-1}		51.4	447.1	204.1	101.6
Lorey’s height, m		7.8	25.4	15.9	4.4
Stem number, ha^{-1}		550	3105	1529.8	101.6
Test data	41				
Volume, m^3ha^{-1}		56.1	502.8	209.9	115.0
Lorey’s height, m		8.8	27.0	16.6	4.3
Stem number, ha^{-1}		511	2790	1410.9	533.6

For ITD, a total of 32 height calibration trees were measured in the winter in 2008 to calibrate laser based tree heights to field measured ones. The dbh, height and tree species of 16 Scots pine and 16 Norway spruce within the high resolution ALS data area but outside the sample plots were registered. To predict tree height in 2004 from laser tree height, linear regression was used to get separate height calibration models for the two tree species. However, in order to get heights of trees in 2004, height increment of three growing seasons had to be first removed. Height increment was also modelled with regression by tree species. The modelling data were obtained from the sample trees of 10th National Forest Inventory (Korhonen et al. 2007), measured in 2004-2006, that were within 50 km from the centre of the test area and that had a measurement for height increment of five years. Three fifths of the predicted five year height increment were then removed from the field measured tree heights to obtain tree heights in 2004.

2.2 ALS data

Two ALS data sets were used: high resolution data was used in ITD and low resolution data in CHD. The ALS data were collected on August 4th, 2004, using an Optech ALTM 2033 laser scanning system. Low resolution dataset covers all the sample plots in the area and its point density is about 0.7 measurements per square metre. Low resolution data was captured at an altitude of 1500 m above ground level (a.g.l.). Four overlapping flight lines were also captured at an altitude of 380 m a.g.l. These four flight lines together with the low resolution data from the same area comprise a high resolution dataset which covers the region of the 41 sample plots used as test data. The point density in high resolution data is about 7 measurements per square metre. The field of view of the laser scanner was 30 degrees in both altitudes.

The low resolution dataset was used to generate a digital terrain model (DTM) to a pixel size of one meter using the method explained in Axelsson (2000). The high resolution dataset was used to generate a canopy height model (CHM) for ITD. First the DTM height was subtracted from the orthometric laser scanning heights and this point dataset was rasterized to a CHM of 40 cm pixel size by taking the maximum point height value within a 28 cm radius from each centre of a pixel. To get a final CHM, the number of missing pixels and low, differing pixels was reduced with a median filtering in local windows of 3 by 3 pixels. First, each missing pixel that had at least n height values (parameter) within its eight-neighbours was replaced with the median of the height values. This was run three times with parameter n having the values 5, 3 and 3. After this, the remaining missing pixels were set to 0. Further, a pixel was considered to be a low, differing pixel, if at least seven of the eight-neighbours were more than five meters higher than the pixel itself. These pixels were replaced with the median of the neighbours that were more than five meters higher.

2.3 Individual Tree Detection

Laser based tree candidates were located and delineated in the CHM using watershed segmentation. Segmentation was done to remove some small tree crown segments, typically belonging to very small trees or caused by missing pixels at the tree crown boundaries. Other than that the method was similar to local maxima finding. Before segmentation, a CHM was low-pass filtered with height based selection of degree of filtering (Pitkänen et al. 2004). Three Gaussian filters were used so that the filter size increased along with the height of the pixel being filtered. The smallest and largest σ values were selected by verifying visually that the number of local maxima was reasonable at both ends of the tree height range. The height ranges and corresponding σ values used were 0-12 m and σ 0.4, 12-24 m and σ 0.6 and over 24 m and σ 0.8.

A negative image of the height filtered image was then created for the watershed segmentation that was used to separate tree crowns from each other. Watershed regions associated with the local minima in the negative image were identified using an algorithm which followed the drainage direction (Gauch 1999, see also Narendra and Goldberg 1980). To get boundaries between crowns and background, pixels lower than two meters in the height filtered image were masked out from the crown segments. Finally small segments, at most three pixels in size, were combined to one of the neighbour segments, be it a tree crown or background, based on the smallest average gradient on the common segment boundary.

Tree locations and heights were then obtained from the location of the pixel with the highest CHM value within each segment. These laser based heights were further calibrated to estimates of field measured tree height using height calibration models. Either the model of Scots pine or Norway spruce was used for all laser based trees within a plot, based on the dominant tree species of the plot, which was assumed to be known. A dbh was predicted for each laser based tree from the height estimate using the models by Kalliovirta and Tokola (2005); South boreal models for either Scots pine or Norway spruce were employed (see table 6, p. 236), again according to the dominant tree species of the plot. Within the plots, only trees with a dbh estimate greater than 5 cm were retained in stem number and other estimates. The volumes of individual trees were calculated from the dbh and tree height estimates using the same models (Laasasenaho 1982) as with the field data and summed at the plot level. Lorey's mean height was also calculated similarly as in the field data.

2.4 Canopy Height Distribution modelling

Orthometric laser scanning heights were transformed to above-ground heights by subtracting the DTM at the corresponding point. The ALS hits were then classified as ground and canopy hits, assuming that points with a canopy height value of less than 2 metres represented ground hits and the remaining points could be considered canopy hits. The first and last pulse height distributions were created from the canopy height hits and different height metrics were calculated for each sample plot. Percentiles for the canopy height were computed for 1, 5, 10, 20, … , 90, 95 and 100 % (h_5,…, h_{100}) (see Næsset 2002), and proportional canopy densities were calculated for each of these quantiles (p_1,…, p_{100}). Furthermore, the proportion of canopy hits vs. ground hits (veg) was computed for each plot. All these characteristics were calculated separately for first and last pulse data, henceforth denoted by the prefix f or l.

Regression models were then constructed for the stand variables volume, Lorey's mean height and stem number, and ALS-based height characteristics were used as independent variables in these regression models. The candidate models, and all their different transformations, were compared to find as linear as possible a relationship between dependent and independent variables by using stepwise regression. The forms of the final models were then chosen on the basis of model accuracy. As it was assumed that the dominant tree species of the plots were known, the information about the dominant tree species was tested as a dummy variable while constructing regression equations.

2.5 Estimated stand characteristics and accuracy assessment

Accuracy assessment was performed with the test data (41 sample plots) that was not used in model creation either in the CHD or ITD. High resolution ALS data was used in ITD and low resolution ALS data in CHD. The stand characteristics mean volume, stem number and Lorey's mean height were estimated for the test plots. The results were validated in terms of relative RMSE and bias at the plot level:

$$RMSE\text{-}\% = \frac{\sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}}{y_{mean}} \times 100\,, \tag{1}$$

$$bias\text{-}\% = \frac{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n}}{y_{mean}} \times 100\,, \tag{2}$$

where *n* is the number of plots, y_i is the observed value for plot *i*, $\hat{y}_i$ is the predicted value for plot *i* and y_{mean} is the observed mean of the variable in question.

3. Results

The variables used in the CHD models were ln(f_h_1), f_h_{70}, ln(l_veg) and l_p_1 for square root of volume, f_veg and l_h_{20} for square root of stem number and f_h_{10} and ln(l_h_{70}) for logarithmic mean height. Bias correction factors were also added to the model predictions. The dummy variable indicating the dominant tree species was not statistically significant in any of the constructed models.

The accuracies of volume, Lorey's mean height and stem number estimates at the plot level are presented in Table 2. ITD and CHD produced almost equally accurate estimates regarding stem volume and Lorey's height. The RMSEs for volume were 21.73% and 21.78% for CHD and ITD, respectively, and the corresponding figures for Lorey's height were 8.33% and 8.35%. The CHD slightly overestimated both volume and height, whereas the ITD slightly overestimated height and underestimated volume. However, bias was minor in both approaches for these two variables.

Stem number estimates were less accurate than the estimates of volume and height, as was expected. The CHD method was able to estimate stem number considerably more accurately than what was achieved with the ITD. The RMSEs of stem number were 27.29% for CHD and 49.12% for ITD. The ITD underestimated the stem number clearly, whereas the bias of the CHD was negligible. However, both methods had a trend in residuals: from sparse to dense plots, the ITD estimates changed from slight underestimates to clear underestimates whereas the CHD estimates changed from overestimates to underestimates.

Table 2: Accuracy of the estimated stand characteristics at the plot level for ITD and CHD.

		Volume	Lorey's height	Stem number
RMSE-%	ITD	21.78	8.35	49.12
	CHD	21.73	8.33	27.29
BIAS-%	ITD	3.00	-2.75	36.55
	CHD	-3.96	-0.25	3.60

The study design enabled the comparison of residuals between the ITD and CHD because stand characteristics were estimated for the same plots. It was especially interesting to compare residuals as a function of stem number because ITD underestimated the stem number in most of the plots, the bias being 37%. Figure 1 depicts the relative error of volume as a function of stem number for the ITD and CHD. Stem volume was selected because it is often the most important outcome of a forest inventory. One could assume that the ITD was more biased in dense forests compared to the CHD. However, there is no observable trend of difference between the ITD and CHD in Figure 1. Thus, error in stem volume does not differ between the ITD and CHD as a function of stem number.

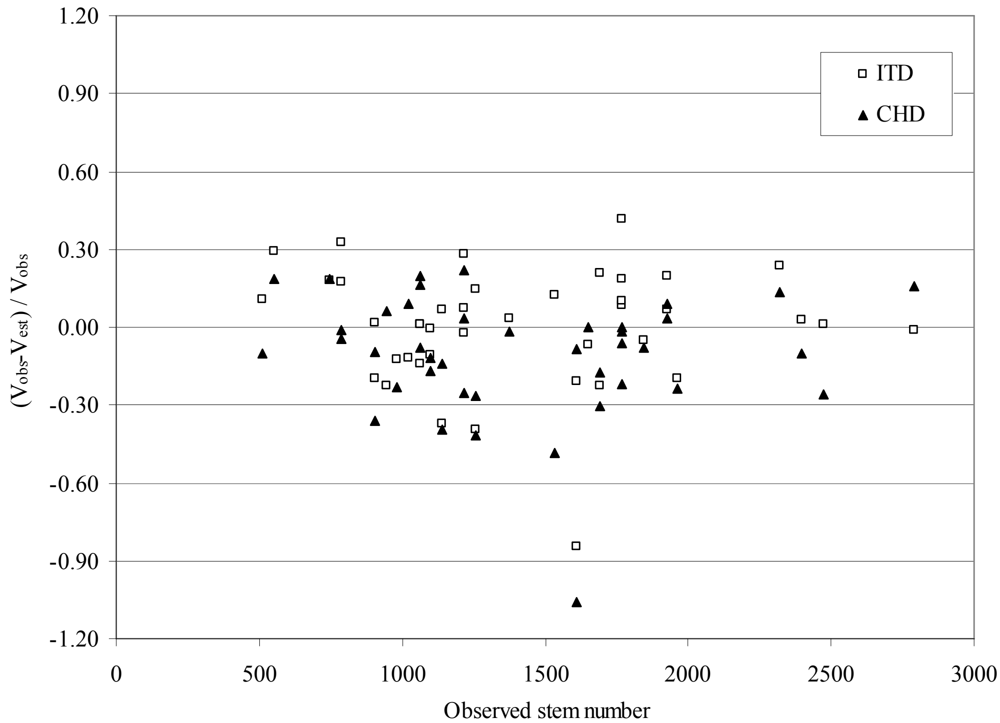

Figure 1: Relative error of volume at the plot level as a function of observed stem number for ITD and CHD. V_{obs} denotes observed and V_{est} estimated stem volume.

4. Discussion

ITD and CHD yielded almost equally accurate estimates for volume and Lorey's mean height. The bias was minor in these variables with both approaches, too. Regarding stem number, ITD was substantially less accurate than CHD and produced notable bias. The obtained accuracies are consistent with earlier studies carried out using CHD based methods in Finland (e.g. Havia 2006, Maltamo et al. 2006). Comparison to earlier works in the case of ITD is difficult since most of the studies done in Finland are carried out on unmanaged seminatural study areas (e.g. Hyyppä and Inkinen 1999, Maltamo et al. 2004). The only exception is the work by Peuhkurinen et al. (2007), in which two mature stands of the current study material were used in pre-harvest inventory by means of ITD. It is also difficult to compare tree and plot level accuracies: in ITD studies, the accuracy assessment is often done at tree level.

This case study indicated that considering volume and mean height both ITD and CHD are potential inventory approaches in managed boreal forest. The results of stem number estimation were not so good, especially with ITD. With this method, the estimates of different variables are based on the same laser detected trees. Thus, there is some contradiction in the result that stem numbers were clearly underestimated but volume estimates were accurate. It is obvious that large, dominant trees, forming most of the stem volume, are more often detected by ITD than small or suppressed trees. Most of the difference is probably explained by this; the same tendency was observed by Persson et al. (2002), for instance. Other possibilities are overestimation of tree heights or dbh of the trees. Data for laser tree height to field tree height calibration was collected three growing seasons after the ALS data, which reduces the accuracy of height calibration. It is also possible that the models used to predict dbh from tree height gave overestimates in this area. However, this is left to be studied in a further work.

Another possibility than accuracy is to compare costs of the inventory methods. Of course the costs of the high pulse density data are higher than those of the low pulse density data. On the other hand CHD methods require more field work. In our study only one field day was used to measure calibration data for ITD, whereas it will take about 1-2 weeks to measure about 50 plots used in CHD. However, we used considerably lower number of modelling plots than in many earlier CHD studies (e.g. Næsset 2002, Maltamo et al. 2006) but the accuracy was still correspondent. It is possible that the amount of reference data could still be reduced in CHD; the more important thing is to find the optimal placement of the sample plots. A cost factor which is very difficult to take into account is the time spent in the analysis. Especially those processing steps, which cannot be completely automated, increase costs. From this point of view CHD is maybe slightly more straightforward.

In Finland the prediction of species specific stand variables is of primary interest but here we only assumed that the main tree species of a stand is known. However, there exist also studies where Scandinavian tree species are taken into consideration. In the case of CHD based methods Packalén and Maltamo (2007) have shown that when ALS data and aerial photograph are combined tree species can also be successfully predicted. In the case of single tree detection there also exist some studies which have considered tree species information (e.g. Holmgren et al. 2008, Ørka et al. 2007, Vauhkonen 2007) but the calculation of tree volumes has not been taken into consideration. Diameter distributions are also of interest in many applications but they are not considered here. Thus, the deductions made in this paper do not take into account the ability of CHD or ITD to estimate species specific stand characteristics or diameter distributions.

The implemented study design enabled the comparison of estimates between ITD and CHD, when typical data sets for both methods were used. In addition to accuracy comparison it is interesting to examine whether they produce similar kind of residual structures or not. This might reveal if one or the other approach is more accurate in some type of forests, in mature or dense stands, for instance. One comparison of this kind was shown in Figure 1. It was also noted that especially in those plots where forest characteristics were estimated most inaccurately there is a clear correlation of residuals between ITD and CHD. This is an interesting observation that needs to be studied further in future.

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