MAPPING DEFOLIATION WITH LIDAR

S. Solberg [a, *], E. Næsset [b]

[a] Norwegian forest and landscape institute, P.O. Box 115, N-1431 Ås, Norway – svein.solberg@skogoglandskap.no
[b] Dept. of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, N-1431 Ås, Norway - erik.naesset@umb.no

KEY WORDS: Leaf area index, LAI, LIDAR, defoliation, woody area

ABSTRACT:
The aim of this article is to present a concept of using airborne laser scanning (LIDAR), with one scan only, to map defoliation as a forest health variable. The idea is to apply two independent algorithms on the LIDAR data set, to produce both actual and expected leaf area index (LAI) values for every cell in a grid over the area. LAI is estimated based on laser pulse penetration through the canopy layer, and expected LAI values are derived from stand density based on position and height of single trees as obtained from a single-tree segmentation algorithm. The results are preliminary findings from four ongoing and related studies. In the first study repeated laser scans had close to equal extinction coefficients for LAI estimation although the instruments and flight specifications were different. In the second study, based on the findings in the first we derived normal LAI values from extisting and large scale data sets with LIDAR and field data. The main independent variable was stand density, defined as the ratio between mean tree height and mean distance between the trees. The ratio between LAI and stand density was around 0.5, and this is a preliminary standard for a healthy pine forest. In a third study the woody area fraction of LAI was estimated from 14 total harvested trees, and turned out to be slightly below 50% for a healthy pine tree, which means that a totally defoliated pine forest would have an LAI/stand density ratio around 0.2. In the fourth study, these LAI standard values were confirmed with LIDAR data from a severe insect defoliation event in Norway 2005. In conclusion, the present preliminary results demonstrate a potential for application of airborne laser scanning for monitoring or mapping of defoliation as a forest health variable.

1. INTRODUCTION

In two test cases with Norway spruce and Scots pine in Norway, it has been demonstrated that airborne laser scanning (LIDAR) can be used for mapping of leaf area index (LAI) (Solberg et al., 2005), and repeated scans can be used for mapping of defoliation events (Solberg et al., 2006a). However, normally defoliation events are not known in advance, and it would be useful to be able to map defoliation based on one laser scanning after a forest damage event. This would be useful for obtaining an overview of the damage area for actions such as sanitary cutting, prevention of further spread of the damage, for forest insurance companies, and for general interests of having damage overviews.

There are some problems that need to be resolved in order to realize such a one-scan defoliation mapping. First, there is a need for data on normal LAI values for the given site and stand properties of the forest in question. Second, the LAI obtained is so-called effective LAI which includes woody areas of branches and stems. Hence, there is a need for knowing the woody area faction of the actual forest, which would be the LAI value for a totally defoliated forest. This woody area is the area of branches and stems. Both the normal LAI values and the woody area will depend on the number of trees and their size. Hence, we see here a potential for modelling both the normal LAI values and the woody area as a function of single-tree data obtained from automated single-tree segmentation routines (Solberg et al. 2006b).

The major objective of this article is to present preliminary results of such a one-scan forest health mapping concept, applying two independent algorithms on the same LIDAR data set. First, LAI is estimated from LIDAR pulse penetration through the canopy layer, and second, expected LAI values are obtained for the forest if it was healthy and if it was totally defoliated based on modelling on single tree segmentation data. One specific aim was to test whether already existing LIDAR data sets could be used to generate normal LAI values, i.e., do technical differences between airborne laser scans influence the extinction coefficient of the laser pulses through a forest canopy layer (Næsset & Solberg, 2007)? A second aim was to generate normal LAI with key stand and site property variables, mainly based on single tree data (Solberg & Næsset, 2007). Third, how can the woody area fraction be estimated (Solberg, 2007a)? The fourth and final aim was to apply the results of the above mentioned steps in a test case with severe insect defoliation on a Scots pine forest (Solberg, 2007b).

2. MATERIALS AND METHODS

Solberg et al. (2006) used calibration from point-based measurements on the ground with LAI-2000 and hemispherical photography to estimate LAI. The calibration was done with the formula:

[1] $$LAI = (1/k) \ln(N_a/N_b)$$

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* Corresponding author

where k is an extinction coefficient, and the term $\ln(N_a/N_b)$ is the inverse of the gap fraction. N_a is the total number of echoes and N_b is the number of below-canopy echoes for a 30m-diameter circle around each ground measurement point.

A number of studies have already addressed the effects of differences between laser data acquisitions using different sensors, flying altitudes, footprint sizes, and sensor specifications on basic laser-derived forest data metrics (e.g. Næsset 2004, 2005; Chasmer et al, 2006). Significant effects of flying altitude, sensor and repetition frequency have been reported, but the influence on biophysical properties may be limited by selecting operational parameters that are similar across acquisitions. For example, the effects of repetition frequency for a given instrument can be more significant than effects of different instruments operated with similar settings (Næsset, in prep). It also seems to be a general tendency for first return data to be more stable across flight specifications than last return data. The current application is based on first return data only. It is therefore not unlikely that the technical properties of the laser scanning turns out to have a limited effect on the extinction coefficient.

2.1 Stability of laser canopy penetration across LIDAR campaigns

In this part of the study, we utilized existing data sets from previous laser data acquisitions of forests in Norway, where the scanning is repeated over the same area with different technical properties. Important here is that we don't need to calibrate the LAI data with ground measurements. It is sufficient to compare the $\ln(N_a/N_b)$ term in equation [1], which is proportional to LAI. This is valid if the laser scanning is repeated for an area and LAI was the same on both occasions.

2.2 Modelling normal LAI values

The idea is that LAI will normally vary with tree species, site index and stand density, where the latter reflects both the number of trees per unit area and the spacing between them. For each species and site index the normal LAI should be proportional to stand density (*SD*) which we initially defined as:

[3] $SD = h/dist$,

where h is the mean tree height, and *dist* is the mean distance between the trees.

We used existing and comprehensive data sets with airborne LIDAR to produce normal values of LAI for Scots pine, and for various values of stand density and site index. We had at hand a considerable amount of extensive airborne LIDAR data sets for forests in Norway. In each of these study areas, a number of field plots with complete measurements of trees and site productivity were available for analysis.

2.3 Correction for woody area fraction

From the forest area with insect attacks in 2005, 14 pine trees were sampled. They were located one in each of 14 sample plots in age classes from young, intermediate age and old stands. The sample trees, having heights of 10-30 m, were felled and all branches harvested. The branches, having a total mass of 591 kg d.w., were dried and separated into needles, twigs, and coarser branches for detailed measurements of hemisurface areas and clumping factors, mainly by photographing techniques (Fig. 1). From the total area, the area fraction of branches and stems, i.e., woody area, was calculated. Also, the woody area was modelled as a function of single-tree measurements, such as tree height and crown width. Such variables might be derived from single-tree segmentation algorithms using LIDAR data.

Figure 1. Example of branch photography.

2.4 Example of the method applied on insect defoliation event

For testing the method, a laser scanning data set covering a 21 km^2 area with severe insect defoliation of Scots pine from 2005 was applied. First, we used the single-tree segmentation algorithm (Solberg et al., 2006b) in order to detect all local maxima in the digital canopy height model (DSM), most likely being tree tops. The entire area was then divided into 10m x 10m grid cells. For each cell, the stand density (*SD*) was calculated based on the height and position of the local maxima. Second, for each cell LAI was calculated according to model [1], where $1/k$ was set to 1.48 (Solberg et al., 2006a). Finally, each grid cell was then provided with a forest health indicator value, *c*, defined as:

[4] $c = LAI / SD$

This health proportionally factor was then assigned to forest health classes based on training sites within the damage area where the degree of defoliation was known based on

a) field observations;
b) changes in LAI during the insect defoliation period June – July obtained by repeated laser scanning;
c) the normal LAI values obtained above from other sites; and
d) minimum LAI values set to woody area as a function of single tree variables.

3. RESULTS

3.1 Stability of laser canopy penetration across LIDAR campaigns

Fortunately, different laser scans had equal extinction coefficients for *LAI* estimation, although the instruments and flight specifications were different (Fig. 2).
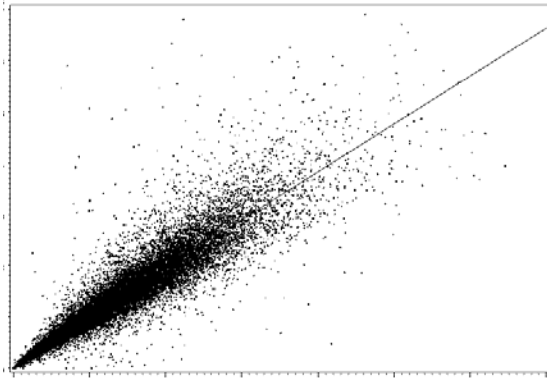
Figure 2. Relationship between $\ln(N_a/N_b)$ for two laser scans done with two different scanners at two points of time over a forest reserve with no forest management. The 1:1 line is shown. The $\ln(N_a/N_b)$ range is 0-7, which corresponds to an LAI range of about 0-14. The spatial resolution is 10m x 10m, n=19399, and the no-intercept model was $Y = 0.98X$.

3.2 Modelling normal LAI values

The result of the modelling of normal LAI values for forests produced quite stable ratios between $\ln(N_a/N_b)$ and stand density values. However, no effect of site index was found. Random errors might be present due to a limited number of plots for the lowest and highest site index classes. The ratios ranged from 0.29-0.38, which would correspond to health indicator ratios (c) in the range 0.43-0.56 after scaling with the $1/k$ factor being 1.48 (Solberg et al. 2006a).

Site index, H40	factor
6	0.34
8	0.37
11	0.32
14	0.29
17	0.38
20	0.32

Table 1. Proportionality factor between $\ln(N_a/N_b)$ and stand density for various combinations of site index for Scots pine.

3.3 Correction for woody area fraction

The woody area fraction was around 50% for those trees not affected by the insect defoliation, and increased to 85% of the area for trees with severe defoliation. The woody area fraction of LAI can be estimated based on regression models with input variables such as crown size and tree height (Table 2). It is notable that crown projected area was a stronger predictor for woody area than tree height, which indicates that the spacing between the trees are important for the amount of branching and woody area.

Variable	Parameter estimate	R^2
Height, m	1.25	0.46
Crown volume, m^3	0.96	0.61
Projected crown area, m^2	2.99	0.83
Crown length, m	2.76	0.47

Table 2. Results of no-intercept regression models for woody area against various tree size measures that were derived from an automated routine for single tree segmentation on the LIDAR data for the 14 sample trees.

3.4 Example of the method applied on insect defoliation event

In total, 1.5 million local maxima were found over the 21 km^2 area, and the process was quite time-consuming with 35 hours computing time with a Pentium 4 processor with a 3.2 GHz clock frequency. From the training sites we obtained different values for the forest health indicator (c). First, the training sites subject to severe defoliation had c values around and lower than 0.25. A second set of training sites consisted of grid cells having no change in LAI from May to August. This is likely to be sites with a moderate degree of defoliation, i.e., where the amount of insect defoliation equalled the amount of new needles produced during the summer. These sites had a mean forest health indicator value $c = 0.32$. Finally, sites where we did not observe any signs of defoliation had c values in the range 0.3–0.6. All these results were from pine-dominated grid cells, having 90% or more of the standing volume being pine.

It turned out that the pine forest in this case was in general quite defoliated, and in order to visualize some spatial variability we produced a map with more arbitrary threshold values for the forest health indicator c (Figure 3):

- Class 1, most defoliated: c < 0.225
- Class 2, moderately defoliated: 0.225 < c < 0.275
- Class 3, least defoliated: c > 0.275.

These values are lower than what was obtained from the normal LAI values, and visualizes degrees of defoliation severity.
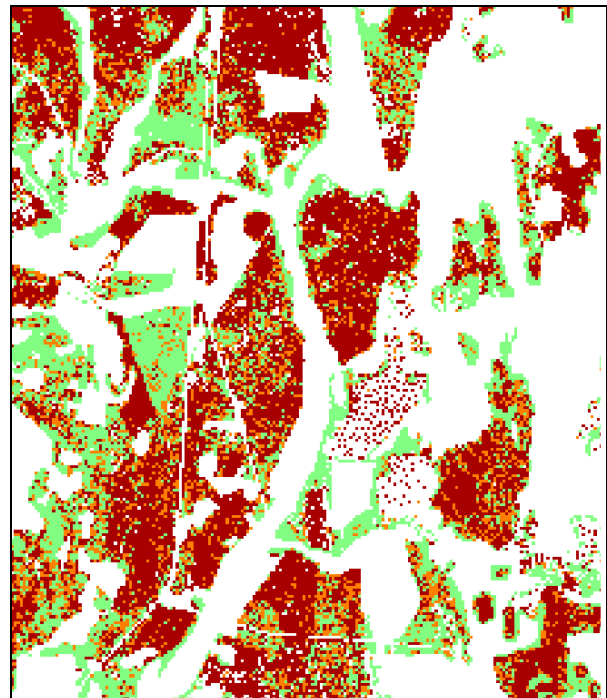

Figure 3. Map of defoliation in 2005 with an extent of 2 km x 2.3 km. Red (dark grey) = severe defoliation; orange (grey) = moderate defoliation; green (light grey) = less severe defoliation; white = areas other than pure pine forest.

4. DISCUSSION

The presented results are all preliminary. However, as a whole, they indicate a potential for using one laser scanning only for mapping defoliation. Two independent algorithms are used to process the laser datasets. First, LAI is estimated based on the degree of laser pulse penetration through the canopy layer. Second, tree heights and locations are derived by a single-tree segmentation algorithm, and these data are recalculated into a stand density variable. Then, a grid with a given spatial resolution is overlaid and the two variables are combined into a *LAI/SD* ratio which can be used as a forest health indicator. It appears that a healthy pine forest should have a *LAI/SD* ratio around 0.5, while a completely defoliated forest would have an *LAI/SD* values around 0.2, which would be woody areas of branches and stems only.

We will fine-tune the results further on. In our model of normal LAI values there is a linear relationship between LAI and tree height, and this needs to be refined. As trees grow in height, and the stand is closed, the canopy will be moved upwards, and LAI should not continue to increase linearly. Hence, we will try other non-linear models for tree height in future work. The denominator in the ratio is the mean distance between the trees, which can be recalculated to the inverse of the square root of the number of stems per unit area, and this is a non-linear function of LAI against the number of trees, which is reasonable.

5. CONCLUSION

In conclusion, the present preliminary results demonstrate a potential for application of airborne laser scanning for monitoring or mapping of defoliation as a forest health variable based on one scan only. Standard threshold values for LAI in healthy forests remains to be developed for various tree species and for various combinations of site index and stand density.

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ACKNOWLEDGEMENTS