COMPARISON OF TERRESTRIAL LASER SCANNER AND SYNTHETIC APERTURE RADAR DATA IN THE STUDY OF FOREST DEFOLIATION

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ABSTRACT:

We present new results from a terrestrial laser scanner (TLS) based investigation on forest defoliation caused by the European pine sawfly (*Neodiprion sertifer*) in a Scots pine (*Pinus sylvestris*) dominated forest. The TLS results are compared with simultaneous ERS-2 Synthetic Aperture Radar (SAR) images in order to investigate the synchronous use of ALS and radar in forest change detection, and search for ground based validation methods for satellite SAR forest monitoring. The TLS and SAR based change detection is compared with visual estimation of the defoliation intensity as percentage of needle loss in the living crown. The agreement in results points out the potential for a combined method. The capability of TLS of deriving changes on the standing tree biomass and defoliation level was also confirmed by destructive, consecutive defoliation operations in laboratory. The biomass of the tree was measured simultaneously with the TLS measurements. The point cloud agreed with standing biomass with 95-99% coefficient of determination implying that terrestrial laser can be a powerful tool for biomass change reporting, and thus, usable for defoliation measurement.

1. INTRODUCTION

1.1 Remote Sensing of Forest Biomass

The international interest in biomass detection is strongly related to forest health and carbon cycle monitoring (Sexton et al., 2009). The need for improved tools for, e.g., carbon monitoring applications, and the shortage of data for accurate biosphere and climate models has been internationally recognized (e.g., Houghton et al., 2009). As the current knowledge on biomass, and particularly the changes related to it are almost entirely based on subjective ground measurements, remote sensing methods are called for. Airborne laser scanning (ALS) is a promising method for biomass detection because of its capability of direct measurement of vegetation structure and stand attributes (Næsset, 2002, Hyyppä and Inkinen, 1999). There are several recent activities and development of methods towards more accurate ALS-based biomass detection (Sohlberg et al., 2006; Zhao et al., 2009; Hawbaker et al., 2009).

1.2 Terrestrial Laser Scanning in Forest Remote Sensing

The environmental applications of terrestrial laser scanner (TLS) are constantly increasing. TLS has been found to be an effective and low-cost monitoring method, and the information on TLS performance and range data accuracy is constantly increasing (see Kaasalainen et al., 2009 for more references). The number of TLS applications is increasing in forest management and agriculture, e.g., in measuring the 3D-structure of trees and vegetation canopies (canopy gap fractions), tree volumes and leaf-area. TLS has been used for modelling of individual trees and canopies in (e.g., Pfeifer et al., 2004; Pfeifer and Winterhalder, 2004; Gorte and Pfeifer, 2004; Hosoi and Omasa, 2006; Fleck et al., 2007; Danson et al., 2007; Xu et al., 2007; Chasmer et al., 2006), and for automatic forest parameter estimation (e.g., Bienert et al 2006a, 2006b, 2007; Aschoff and Spiecker, 2004; Király and Brolly, 2007). The use of TLS has recently been extended into mobile methods, namely vehicle-based laser scanning, because of their efficiency in producing large amounts of high-resolution data and strong future potential for different applications (Jaakkola et al., 2008).

1.3 SAR-based Forest Remote Sensing

A large number of SAR-based methods have been created for detection of forest parameters, such as canopy height (Garestier et al., 2008; Sexton et al., 2009). E.g., airborne polarimetric SAR has been found a promising method for estimating the forest structure and tree height (Garestier et al., 2009). In comparison with radar, LiDAR, and field measurements, Sexton et al. (2009) found that the LiDAR measurement produced the best accuracy in pine forests, while the interferometric (SAR) showed potential for LiDAR based calibration. In their investigations of radar-LiDAR synergy, Nelson et al. (2007) emphasized the efficiency of LiDAR in producing accurate and precise biomass estimation and improving the accuracy of radar data. While laser scanning produces higher resolution and accuracy, radar methods are less weather-dependent and capable of producing data from large areas with high temporal resolution (Holopainen et al., 2009b). Holopainen et al. (2009a) compared E-SAR, Landsat Extended Thematic Mapper (ETM) and aerial photographs in estimation of plot-level forest variables and reported relative root-mean-squared-errors (RMSEs) for E-SAR of 45%, 29%, 28% and 38% for volume (m3/ha), mean diameter (Dg; cm) , mean height (Hg; m) and basal area (BA; m2/ha), respectively. In combining E-SAR with aerial photographs, the relative RMSEs for the same variables were 38%, 26%, 23% and 33%.

This article presents first results from a TLS-based investigation on forest defoliation caused by the European pine sawfly, specialist feeder consuming mature needles of pine trees early in

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the season (Viitasaari and Varama, 1987). The TLS results are compared with simultaneous ERS-2 SAR images in order to investigate the synchronous use of LiDAR and radar in forest change detection, and search for validation methods for SAR. SAR data are available from large areas and better temporal resolution than laser data, but because of their higher accuracy, laser-based methods would provide an efficient validation for SAR change detection and forest parameter estimation. This requires a systematic comparison of simultaneous data from both sensors.

2. METHODS

2.1 The Study Site and the Pine Sawfly Hazard

This study was a part of ongoing monitoring campaign for forest defoliation caused by pine sawflies (Diprionidae). The traditional monitoring methods have been based on field sampling (e.g., manual collection of different life stages) and subjective visual observation of tree condition. The test site was located in Outokumpu, eastern Finland, in a Scots pine dominated forest. Reference data were collected from 20 field plots (consisting of 526 trees in total) in June 6-9, 2009. The visual assessment of defoliation was carried out simultaneously with tree-wise measurements in the field plots, and an additional visual assessment was done after defoliation by sawfly larvae (July 26-28, 2009) (see Lyytikäinen-Saarenmaa et al., 2006; De Somviele et al. 2007 for more details).

2.2 Terrestrial Laser Scanning

The terrestrial laser scanner used in this study was Leica HDS6000, a 685nm phase-based continuous wave laser scanner with a 360°×310° field-of-view. The distance measurement accuracy is 4-5mm and the angular resolution is selectable from full 0.009° down to 0.288°. The circular beam diameter at the exit and the beam divergence are 3 mm and 0.22 mrad, respectively. The scanner uses a silicon Avalanche Photo Diode (APD) as a photo detector.

Two sets of TLS measurements were carried out in the study site in June 25 and July 26-27 during the active period of the pine sawfly hazard. The first measurement was made at the early phases of defoliation and the second one after defoliation period. The scanning was performed from the centre of each field plot with similar scanning parameters and resolution at both dates. Directly visible trees (i.e., those not obscured by other trees) were extracted from the resulting laser point clouds, and the change in the number of laser returns from each tree was compared to the visually estimated defoliation intensity. The defoliation intensity of trees at each field plot was visually assessed and expressed as a relative percentage of needle loss compared with a reference, imaginary tree with full, healthy foliage. The difference from the reference was expressed in incremental defoliation classes of 10%. For full details of this standardized method, see Eichhorn (1998).

The capability of TLS of deriving changes on the standing tree biomass and defoliation level was verified by destructive, consecutive defoliation operations by two different laboratory case studies. In the first case study, one Scots pine tree was defoliated (by picking the needles) in the laboratory in 7 steps. The biomass of the tree (i.e., the mass of the picked needles, and in the end also the stem and branches) was measured simultaneously with the TLS (the scanner located beside the trees), and defoliation was also estimated visually. Three simple tree-wise parameters were derived to represent the tree quality and defoliation: number of echoes coming from the tree, ratio of tree hits (i.e., number of echoes coming from the tree divided by the total number of echoes), and the number of echoes from the ground. These parameters were compared with the tree biomass (in grams) measured with a 2-g accuracy for each step.

In the second laboratory experiment, five pine (Scots Pine) and spruce (Norway Spruce, *Picea abies*) trees were measured with TLS from above and below. Here too the biomass of the tree was measured simultaneously with 2-g accuracy. The biomass was measured in five steps for each tree resulting in 50 samples of biomass/defoliation.

2.3 SAR Image Analysis

The Outokumpu research site was also investigated from the ERS-2 SAR images. ERS-2 is an Earth observation satellite of the European Space Agency launched in 1995. One of its main instrument is SAR, which uses C band microwave radiation (wavelength of about 5.6 cm). The spatial resolution of SAR in the image mode (PRI) is about 25 metres in range and 21 metres in azimuth direction. Some of the main functions of the satellite have damaged preventing for example the interferometric processing in some cases, but the radiometric stability of the PRI images is still expected to be fine (Meadows et al., 2008). The reason for using ERS-2 images was their availability in the ESA image archive.

Satellite	Pass	Track	Frame	Date
ERS-2	Descending	93	2336	11 Aug 2008
ERS-2	Descending	93	2336	15 Sep 2008
ERS-2	Descending	93	2336	20 Oct 2008
ERS-2	Descending	93	2336	18 May 2009
ERS-2	Descending	93	2336	22 Jun 2009
ERS-2	Descending	93	2336	27 Jul 2009
ERS-2	Descending	93	2336	31 Aug 2009

Table 1. List of used ERS-2 SAR images.

Altogether 7 images were acquired through the ESA Category-1 project (Table 1). Topography is known to have a strong effect on the observed backscattering. Therefore, we decided to use images with the same imaging geometry (same satellite pass direction and track). However, the weather conditions during the acquisition, as well as the soil surface and vegetation moisture values of the test plot, are not known. Therefore, it can be expected that there is variation in the backscattering values of the test plots between the images. All images were ordered as detected products (PRI images), so only the amplitude information of backscattering signal is used in the studies (non-interferometric data).

First, all input images were co-registered with each other with sub-pixel accuracy. The image of 11 August 2008 was used as a master image. Then, the stack of images was georeferenced into the Finnish map coordinate system (ETRS-TM35FIN) using Ground control points and Digital elevation model. According to the image coordinate residuals the accuracies of 0.8 pixels and 0.4 pixels were achieved in the range and azimuth coordinate directions, respectively. A false colour fusion of all input images is presented in Figure 2, where blue areas correspond to the water bodies. The city of Outokumpu is located in the bottom right corner of the Figure 2.

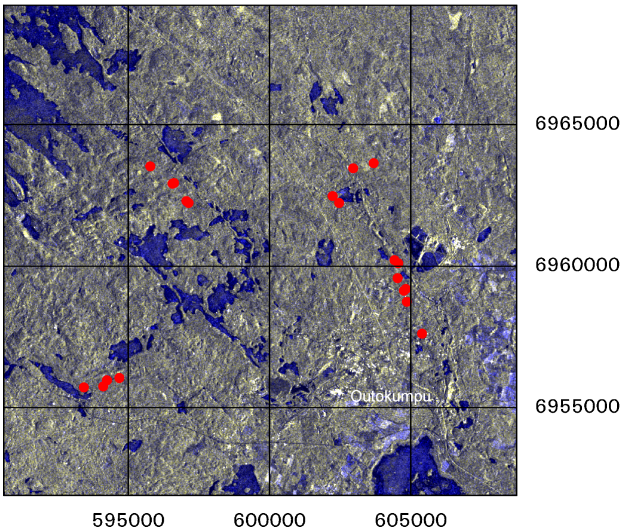

Figure 2. Fusion of all input SAR-2 images. Red dots present the locations of the test plots (Red+Green: Mean amplitude of all images, Blue: Standard deviation of amplitude in input images). Map coordinate system: UTM35N/WGS84. Original data © 2008-2009, European Space Agency.

3. RESULTS

3.1 TLS Laboratory Measurements of Biomass Change and Defoliation

In the first laboratory measurement with the used three predictors, the Pearson correlation coefficients derived were 0.996, 0.977 and 0.929, respectively, which implies that the change in the number of points reflected from the tree represent accurately the change in the standing biomass of the tree. The correlation with the estimated visual defoliation was much smaller. Thus, the changes of the pine biomass could be accurately determined by the change of the laser points in multi-temporal TLS surveys. In this test the reduction of needles from the tree was linear to the reduction of the hits from the tree. In practice, we expect that the process could be non-linear or it could depend on tree species and density of the trees.

In the second laboratory experiment consisting of 10 trees (five pines and five spruces), we used the relative number of hits coming from each tree as a predictor (normalized into 1 when no defoliation has occurred) as learnt from the first experiment. The TLS position (two scanners, one above and the other from below) did not affect the results neither did the tree species. The coefficient of determination with a linear regression model was 0.95 for total biomass and 0.97 for needle and branch biomass (Figures 3 and 4), which implies that the relative number of points reflected from the tree represent accurately the relative standing biomass of the tree. There was some non-linearity in the response, especially with lower relative number of hits, and with a non-linear model the results could be improved.

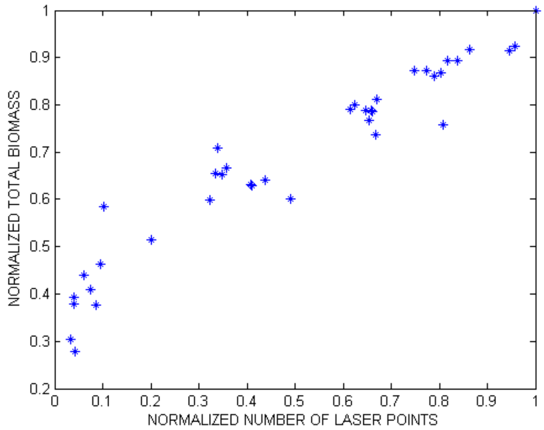

Figure 3. Laboratory experiment: normalized laser point number versus normalized total biomass of the trees. R^2=0.95.

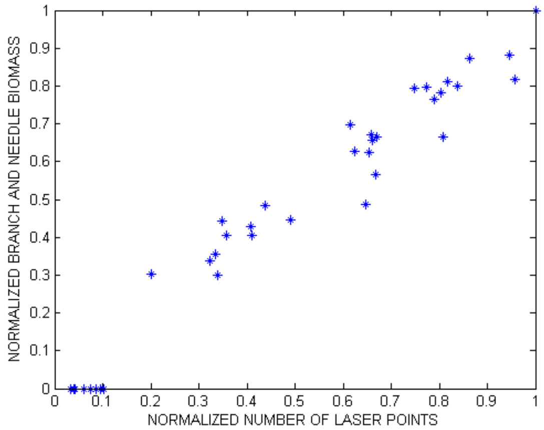

Figure 4. Normalized laser point number versus normalized branch and needle biomass of the trees. R^2=0.97.

3.2 TLS Field Experiment

The change in laser returns from the tree canopy (in percentages) between the measurements in June 25 and July 26-27 is presented in Figure 5 and compared with visual observation. Clear trends of defoliation are visible in both visual and TLS-based analysis of the tree canopies. There are several factors that affect the accuracy, e.g.,

- Deviation in change detection data from TLS point clouds (e.g. mixed pixel effect caused by the phase-based scanning technique)
- The first visual estimation was carried out in June 6-9, i.e. two weeks before the first TLS measurements. During the time difference, the youngest larval instars were already consuming needles.
- The visual estimation of defoliation is subjective (compared to, e.g., laboratory measurements, for which the accuracy is better, see Sect. 3.1)
- The ground-based TLS measurement is made in the upward direction, preventing some parts of the canopy from being measured. Measurement facing downwards (e.g., ALS or unmanned aerial vehicle (UAV) based TLS) would improve the accuracy.

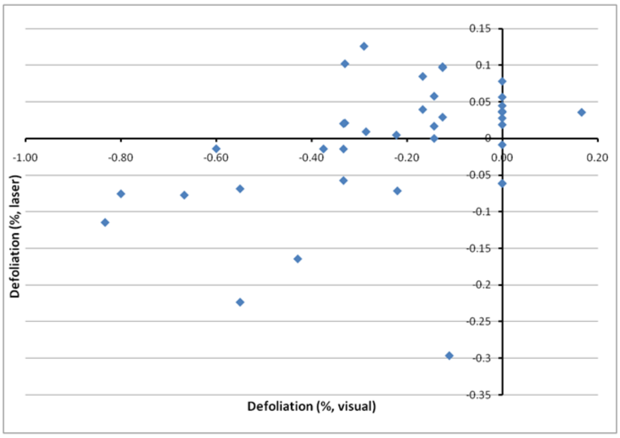

Figure 5. Visual and TLS-based measurement of forest defoliation (in percentages).

3.3 SAR

The change in the ERS-2 backscattering values (amplitude values) of the test plots in comparison with defoliation intensity in late July 2009 is presented in Figure 6. The backscattering values were averaged from the SAR pixel values using a circle with the radius of 50 metres. The test plots were located in the centre of the circles. It should be noted that the spatial and temporal pattern of defoliation, i.e., the focal point and the damage intensity change each year, so the defoliation is not uniform. Therefore, averaging strongly generalizes the results concerning the defoliation. However, averaging was the only way to reduce SAR speckle, and therefore this result is preliminary.

According to the results of 19 test plots, a slight change in the averaged SAR backscatter occurred for the plots with visually observed defoliation. Little or no change in backscatter was observed for those plots where (visual) signs of defoliation were not present. Nevertheless, more test plots for ground reference and SAR data are needed to find out the role of possible other factors to these changes.

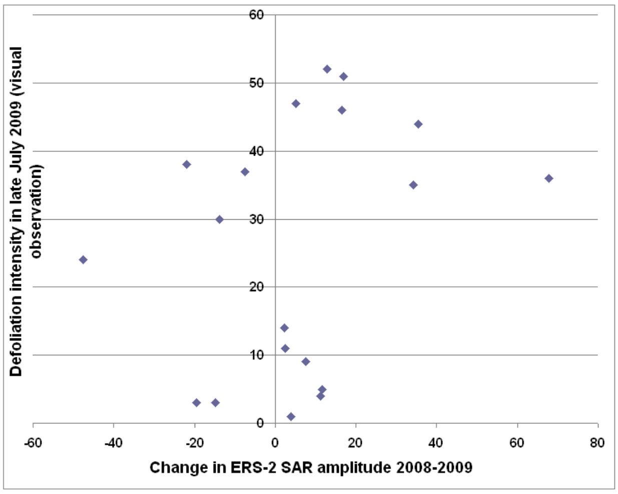

Figure 6. Scatterplot of defoliation intensity (in percentages) in 2009 and change in ERS-2 backscattering (2008-2009).

Because of the qualitative nature of these first results, comparison between TLS and SAR is difficult, but the similarity in results suggests that combined use of these two methods would provide the best time resolution in long-term monitoring applications. In their earlier study, Holopainen et al (2010) compared the accuracy of ALS, multi-temporal high-resolution non-interferometric TerraSAR-X (TSX) radar data and combined feature set derived from these data in the estimation of forest variables (mean volume, basal area, mean height, mean diameter and tree species-specific mean volumes) at plot level. The combined feature set marginally outperformed the ALS-based feature set. Features from TSX alone performed poorly, but brought some extra information into the combined set. However, due to favourable temporal resolution, they concluded that satellite-borne radar imaging is a promising data source for updating large-area forest inventories based on ALS.

CONCLUSIONS

The defoliation trend was visible in the TLS laboratory and field experiments, and SAR data for those plots where defoliation was observed visually. Based on these results and the earlier similar findings (Holopainen et al., 2010), there is great potential in synchronized use of laser scanner and SAR in change detection and forest parameter estimation. This requires careful planning and timing of all experiments for simultaneous data from both sensors and ground reference.

Future tests will show whether the effect of the trunk is important. The results partly explain why ALS has been very effective in earlier studies for stem volume estimation. ALS does not measure only height information, but also direct metrics for biomass, or at least for biomass change. Future tests are needed to verify this, but our results integrated with earlier findings propose that laser scanner measures directly tree height, crown area and biomass with a relatively high accuracy.

The laboratory results point out the better accuracy of TLS measurements, but SAR data are available from large areas and better temporal resolution than laser data. Therefore a combined approach would often produce a larger coverage of observations both spatially and temporally. Also, a shorter wavelength in SAR (X-band, 3.1 cm, as in TerraSAR-X or Cosmo-SkyMed) might be better than the C-band (5.6 cm) used in this experiment.

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