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A nationwide forest attribute map of Sweden predicted using airborne laser scanning data and field data from the National Forest Inventory

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ABSTRACT

The National Mapping Agency in Sweden has conducted an airborne laser scanning (ALS) campaign covering almost the entire country for the purpose of creating a new national Digital Elevation Model (DEM). The ALS data were collected between 2009 and 2015 using Leica, Optech, Riegl, and Trimble scanners and have a point density of 0.5–1.0 pulses/m^2. A high resolution national raster database (12.5 m × 12.5 m cell size) with forest variables was produced by combining the ALS data with field data from the Swedish National Forest Inventory (NFI). Approximately 11500 NFI plots (10 meter radius) located on productive forest land, inventoried between 2009 and 2013, were used to create linear regression models relating selected forest variables, or transformations of the variables, to metrics derived from the ALS data. The resulting stand level relative RMSEs for predictions of stem volume, basal area, basal-area weighted mean tree height, and basal-area weighted mean stem diameter were in the ranges of 17.2–22.0%, 13.9–18.2%, 5.4–9.5%, and 8.7–13.1%, respectively. It was concluded that the predictions had an accuracy that were at least as good as data typically used in forest management planning. Above ground tree biomass was also included in the national raster database but not validated on a stand-level.
An important part of the project was to make the raster database available to private forest owners, forest associations, forest companies, authorities, researchers, and the general public. Thus, all predicted forest variables can be viewed and downloaded free of charge at the Swedish Forest Agency's homepage (http://www.skogsstyrelsen.se/skogligagrunddata).

1. Introduction

Sweden's land area covers 41 million ha, of which 22 million ha is productive forest land that can produce at least one cubic meter of wood per hectare and year. The productive forest land is mainly used for production of timber and pulpwood; approximately 40% of the growing stock is Norway spruce (*Picea abies*), 40% is Scots pine (*Pinus sylvestris*) and the remaining 20% is mostly broad-leaved species, in particular Birch (*Betula* spp.; Skogsdata, 2015). Fifty percent of the productive forest land is divided into 227,000 privately owned estates and the other 50% is owned mainly by a few large companies and the state.

The sample plot based National Forest Inventory (NFI) carried out by the Swedish University of Agricultural Sciences (SLU) is the most important data source for obtaining objective statistics regarding the forest resources on a national and regional level (Axelsson et al., 2010). However, planning of forestry operations needs more localized descriptions of the forest resources than the NFI can provide. In Sweden, stand level data for forest management planning has traditionally been obtained using subjective field inventory methods (Ståhl, 1992). Forest management plans are the property of the land owner and thus are not publicly available.

The development of airborne laser scanning (ALS) has made it possible to produce accurate wall-to-wall predictions of forest variables such as tree height, tree biomass, and stem volume using ALS data (e.g., Næsset, 2002; Holmgren, 2004; Lim and Treitz, 2004; Packalén and Maltamo, 2007). Research in the Nordic countries shows that mean height and volume can be predicted for stands with a relative root mean square error (RMSE) of 3.0–6.4% and 9.3–16.6%, respectively, by combining ALS and field data (Næsset et al., 2004). Both parametric and non-parametric methods have successfully been used for the prediction of forest variables (e.g., Næsset, 2002; Packalén and Maltamo, 2007).

For large area projects, such as making predictions of forest variables for entire nations, ALS data might be trained with sample plot data from existing NFIs. Such projects have so far only been carried out in a few countries. Hollaus et al. (2009) report results for raster based stem volume predictions of 970 km^2 of forest land in the state of Vorarlberg in

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Austria. The reference data used were 96 plots from the Austrian NFI. Since that time, raster predictions of stem volume have been made for all of Austria using a similar method. Denmark has mapped volume, above ground biomass and total biomass across the nation by combining ALS data and field data from the Danish NFI (Nord-Larsen and Schumacher, 2012). In these two countries the ALS based wall-to-wall predictions have, however, been made available for authorities only.

In Sweden, the National Mapping Agency (Lantmäteriet) has carried out an airborne laser scanning of almost all of Sweden for the purpose of creating a new national Digital Elevation Model (DEM). In Southern Sweden, where broadleaved trees occur more frequently than in northern Sweden, the scanning was primarily conducted during leaf-off conditions in order to get the best possible DEM for that region. The ALS data collected are available free of charge to authorities, and at a low cost to the private sector.

In order to stimulate activities in the forest sector, especially among private forest owners, increased availability of up-to-date and accurate spatial information about forest resources was seen as beneficial by the Swedish government. The government recognised that data from the national laser scanning campaign could deliver such information and therefore provided funding for the production of a nationwide forest raster database based on these laser data. The project was led by the Swedish Forest Agency, which is the national authority for supervising the forest sector, and was done in cooperation with SLU, which developed the methodology and generated the database. This article presents the methods and results of this large area project, which represents the largest forest area predicted with ALS data to-date and where the data are distributed freely over the internet.

The objective of the project was to produce and distribute a nationwide high resolution raster database (12.5 m grid cell size) with key forest variables for productive forest land by combining ALS data and field data from the Swedish NFI. The predicted variables were stem volume (m^3/ha), above ground tree biomass (ton/ha), basal area (m^2/ha), basal-area weighted mean tree height (dm), and basal-area weighted mean stem diameter (cm). Additional map products such as soil wetness maps and slope maps were also derived from the ALS data; this was done by different organisations in the project, but they are not described in this article. A description of all products within the project is given in Larsson et al. (2015). An important part of the project was to make the produced datasets openly available for the benefit of private forest owners, forest owner associations, forest companies, authorities, and others.

2. Materials and methods

2.1. NFI data

The Swedish NFI is carried out as two independent, annual, systematic field samples with random placement covering all of Sweden (Ranneby et al., 1987; Fridman et al., 2014). Each field sample consists either of temporary or permanent plots located in square or rectangular clusters. The country is divided into five strata with decreasing sampling intensity towards the north. The side length of the clusters varies from 300 m in the south to 1800 m in the north and the distance between plots within a cluster varies from 300 m in the south to 600 m in the north. Approximately 9500 sample plots belonging to 1100 clusters are field surveyed annually. Of these, 60% are permanent plots that are revisited every five years while the remaining 40% are temporary plots that are measured only once. Trees are callipered on different concentric plot sizes depending on the diameter at breast height (*dbh*) of the trees (Fig. 1).

A large number of forest variables are measured or estimated on each plot, including basal-area weighted mean tree height, basal-area weighted mean stem diameter, basal area, stem volume and above ground tree biomass. The plots are positioned with GPS receivers (Garmin GPSMAP 64) which have a horizontal positional accuracy of

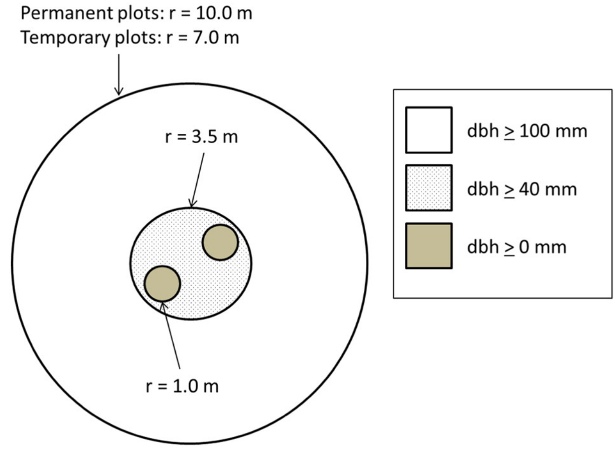

Fig. 1. Sample plot design used in the Swedish NFI since 2003. Note that trees with a diameter at breast height (dbh) of 100 mm or more are measured using different plot sizes on permanent and temporary plots.

approximately 5 m. Gobakken and Næsset (2009) have shown the importance of having accurate plot locations when predicting forest variables such as mean tree height and stand volume based on ALS data. Thus, permanent plots located in productive forest (and not on boundaries between different stands or between different land use classes) were revisited and new coordinates were recorded using high precision GPS receivers (Spectra Precision MobileMapper 120) giving a positional accuracy of about 1 m. Since it is time consuming and costly to revisit the plots and since the budget was limited, it was not possible to collect new, more accurate plot coordinates for all permanent plots within the limits for this project. Tests indicated that the need for highly accurate plot positions was more critical in southern Sweden where the forest landscape was more fragmented and had larger diversity, and less so in northern Sweden where the spatial variation was smaller. Thus, the collection of more accurate plot coordinates was conducted mainly in southern Sweden. In total 3051 permanent plots were given new plot coordinates and used in the project. The plots that were given new plot coordinates covered most parts of southern Sweden except for the coastal part in southeastern Sweden.

Evaluation results indicated that the most accurate ALS predictions in terms of RMSE for stem volume and basal-area weighted mean tree height in all parts of the country were obtained using only permanent plots, with the exception of Gotland where there were too few permanent plots. This is in agreement with the results presented by Gobakken and Næsset (2009) who showed that it is better to use large plots than small plots and that larger plots are less sensitive to positional errors than small plots. Thus, 11,500 permanent plots located on productive forest land that had been field surveyed between the years 2009 and 2013 were used for the production of the national raster database with predicted forest variables. In permanent clusters, there were four or eight plots with a distance between plots ranging from 300 m to 600 m, with the smallest distances between plots in southern Sweden and the largest in northern Sweden.

The forest conditions on the island of Gotland are unique due to different soils and climate as compared to the rest of Sweden. It was therefore decided that only field data from the island should be used to estimate the regression models used for the prediction of forest variables there. Since there were only 78 permanent NFI plots available in Gotland, an additional 87 temporary plots were used for the prediction of forest variables.

The NFI plot data were either forecasted or backcasted to the same year as the plot was laser scanned. This was done using growth models implemented in the Heureka forest planning system developed at SLU (Wikström et al., 2011). Thus, all forest variable predictions relate to the year of scanning. The growth models implemented in Heureka are

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