Estimating Forest Age and Site Productivity using Time Series of 3D Remote Sensing Data

ESTIMATING FOREST AGE AND SITE PRODUCTIVITY USING TIME SERIES OF 3D REMOTE SENSING DATA

Jörgen Wallerman[1], Kenneth Nyström[1], Jonas Bohlin[1], Henrik J. Persson[1], Maciej J. Soja[2] and Johan E. S. Fransson[1]

[1]Swedish University of Agricultural Sciences, Department of Forest Resource Management, Umeå, Sweden
[2]Chalmers University of Technology, Department of Earth and Space Sciences, Gothenburg, Sweden

ABSTRACT

Three-dimensional (3D) data about forest captured by airborne laser scanning (ALS) have revolutionized forest management planning. Accurate, updated large-scale maps of forest variables produced with low costs today support greatly improved decisions about silvicultural treatments compared to the past practice based on field surveyed data only. These maps usually lack important information about forest age and site productivity, as this cannot be accurately assessed from the available ALS data. In Sweden, ALS has recently been performed nation-wide, except the mountainous area, to produce a new and accurate digital terrain model (DTM). This DTM enables extremely cost-efficient extraction of 3D data about the forest from other sources than ALS, such as automatic stereo-matching of aerial images as well as from single-pass spaceborne interferometric synthetic aperture radar (InSAR). In contrast to ALS, these data sources can provide low-cost time-series of 3D data. Aerial images of Sweden are often available in archives back to approximately 1960, and the TanDEM-X SAR system has the potential to provide new data every second week over large areas. These data have a potentially high value for forest management planning, since they may provide missing and highly important information – forest site productivity, Site Index (SI) and forest age. This pilot study explores a least-squares minimization approach to estimate forest age and SI from time series of 3D data produced by 1) image matching of DMC aerial images, and 2) TanDEM-X SAR data.

Index Terms— Forestry, site index, 3D data, aerial photography, radar

1. INTRODUCTION

In most forest management operations, large efforts are made to plan applications of silvicultural treatments for each forest stand in order to optimize the total production of wood products. In support of this process, it is necessary to have access to fundamental data about the stand level attributes, such as tree species composition, stem volume per hectare, mean tree height and mean stem diameter for each stand within the entire holding. In order to apply correct treatments, and to make accurate prognoses of forest development, it is vital to also have accurate data about the forest site productivity. Forest site productivity is defined as the soil's inherent capacity to produce wood volume, i.e. the mean annual production of stem volume per hectare for a well managed forest growing on the particular site. A commonly used indirect measurement of forest site productivity is the Site Index (SI), which is the average height of the dominant trees per hectare at a given reference age (in Sweden commonly the 100 thickest trees at 100 years). SI can be assessed using existing height development functions, which describe the expected mean tree height at any given forest age for each SI class. In the modern Swedish forestry airborne laser scanning (ALS) has revolutionized data capture of the forest for management planning purposes. The 3D data produced are used to make accurate forest variable estimations with high spatial resolution for very large areas. However, a suitable cost efficient method to derive SI for large areas do not yet exist.

In the recent years Lantmäteriet (the Swedish National Land Survey) has carried out an ALS campaign covering Sweden (not yet for the mountainous region) in order to produce a new and accurate digital terrain model (DTM). The new DTM opens up new possibilities to cost efficient acquire accurate 3D data of the forest using several other remote sensing techniques than airborne laser scanning [1-2]. These techniques accurately measure the height of the forest canopy top surface, but do not at the same time provide the accurate DTM data needed to estimate forest height.

Given the accurate DTM, it is possible to assess time series data about the forest height development – data that could potentially be used to produce high-resolution maps of SI for all forested parts of Sweden. Such accurate 3D data of the forest can be extracted using stereo matching of standard aerial images [1, 3], and since Sweden has been covered by repeated aerial photography missions for at least sixty years there is a large potential to accurately map SI using long time series of data. In addition, through the spaceborne radar TanDEM-X system (consisting of two almost identical twin satellites operating at X-band) developed by the German Aerospace Center (DLR) accurate forest height estimates can be made using single-pass interferometric synthetic aperture radar (InSAR) technique given an accurate DTM [2]. Since SAR is an active technique the 3D data can be retrieved regardless of weather and illumination conditions with a high repetition frequency from the spaceborne platform.

The aim of this study is to evaluate the accuracy of site index and forest age estimations using height development data of the forest extracted from 1) a nine year long time series of stereo matched standard aerial images, and 2) a four year long time series of InSAR forest heights.

2. MATERIAL

This study was made using data from the test site Remningstorp. It is a forest holding located in southern Sweden (Lat. 58°30’ N, Long. 13°40’ E) and covers about 1,200 ha of productive forest land divided into 531 stands. The prevailing tree species are Norway spruce (*Picea abies* (L.) H. Karst.), Scots pine (*Pinus sylvestris* L.) and birch (*Betula* spp.). The dominant soil type is till (i.e., a mixture of glacial debris) with a field layer consisting of different herbs, blueberry (*Vaccinium myrtillus* L.), and narrow leaved grass (e.g., *Deschampsia flexuosa* (L.) Trin.). In denser old spruce stands the field layer is absent. The ground elevation varies moderately between 120 m and 145 m above sea level. The Remningstorp holding is managed by Skogssällskapet and further descriptions of the property are presented in [4].

At Remningstorp, circular field plots (10 m radius) were objectively surveyed in 2010 using a grid sample design, which was a regular quadratic grid with 200 m spacing between adjacent plots over the major part of the estate. The origin of the grid was allocated randomly. Each plot was surveyed using the methods and state-estimating models of the Heureka system [5]. For plots with basal area-weighted mean tree height less than 4 m or basal area-weighted mean stem diameter at breast height (i.e., 1.3 m above ground) less than 5 cm, height and species of all saplings and trees were recorded. For the remaining plots, callipering of all trees at breast height including only trees greater than 5 cm in diameter, and sub-sampling of trees to measure height and age, were performed. Heights of remaining callipered trees on the plots were estimated using models relating tree height to diameter. Site index was assessed at each plot using vegetation and site properties [6]. Plot location was measured using differential GPS producing sub-meter accuracy. In total, 263 plots were measured. The plots were re-surveyed in 2014 and where applicable, SI was also assessed using height development curves [7]. Here, only the 107 plots with SI determined by height development curves were used, since it is the most accurate method. At these plots the basal area-weighted mean tree height in 2010 varied between 7.0 and 27.9 m, with an average of 18.9 m.

A second set of field data was derived from the Swedish National Forest Inventory (NFI) [8]. This dataset was used for developing height development models valid for the Remningstorp area. The NFI each year surveys almost 10,000 field plots across the land area of Sweden. A majority of the plots are permanent, i.e. revisited every fifth year.

Aerial images were acquired by the DMC digital aerial photograph camera [9] operated by Lantmäteriet at six different survey campaigns, with partial or complete cover of the study site (Table I). All datasets were acquired at 4,800 m above ground level (a.g.l.) except for the 2003 dataset which was acquired at 3,000 m a.g.l., resulting in a ground sampling distance of approximately 0.48 m and 0.30 m, respectively. The photographs were acquired with 60% along-track overlap and 30% across-track overlap, resulting in at least one stereo model for each position on the ground. The images were block triangulated using bundle adjustment and radiometrically corrected by Lantmäteriet, as part of their operational aerial image production. Image matching of the digital aerial photographs was performed using the SURE software [10-11] to produce point cloud data for each dataset. SURE generates a height value for each pixel using cost-based matching, similar to the semi-global matching method [12]. Finally, the point cloud height values were transformed from height above sea level to height above ground level by subtracting the ground height. The ground height was extracted from the DTM (2 m grid size) produced by Lantmäteriet using ALS [13].

TABLE I
Utilized DMC aerial photographs

Acquisition date	Altitude	Vegetation season
2003-10-13	3,000 m	leafs on
2005-06-28	4,800 m	leafs on
2007-05-26, 2007-06-03	4,800 m	leafs on
2009-09-01	4,800 m	leafs on
2010-05-02	4,800 m	leafs off
2012-05-23	4,800 m	leafs on

TABLE II
Utilized TanDEM-X image pairs

Acquisition date	Polarization	Vegetation season
2011-06-04	VV	leafs on
2012-06-01	VV	leafs on
2013-07-02	VV	leafs on
2014-06-08	VV	leafs on

The four TanDEM-X images used were all acquired in strip-map mode with VV polarization during 2011-2014 (Table II). The images have been processed interferometrically to generate canopy height models (CHMs) on each field plot out of the interferometric phase and coherence data. The CHM generation used non-linear regression on the form of (Eq. 1) and the parameters were chosen to fit ALS percentile 99 as good as possible (the same parameters were used for the entire test site).

$$\mathrm{p99} = \mathrm{C} \cdot \mathrm{IH}^{\alpha} \cdot \mathrm{COH}^{\beta}, \quad (1)$$

where C is a scaling constant, IH the interferometric height, COH the interferometric coherence, and α and β are exponent variables to be fitted by the model.

Non-linear height development models (Eq. 2) were fitted to the NFI survey data using the NLIN procedure in the statistical software SAS.

$$\mathrm{H} = \alpha_1 \mathrm{SI}(1 - \mathrm{e}^{-\alpha_2 \mathrm{AGE}})^{\alpha_3}, \quad (2)$$

where H is the basal area-weighted mean tree height, SI is the site index determined using site factors and AGE is the basal area-weighted mean tree age. Two separate models were developed, one for pine forest and one for spruce. The CHMs captured by 3D remote sensing data are not equivalent to H, though, but rather the height of the dominant trees. Here, the CHM data were used as an approximation of the mean height of the 100 thickest trees per hectare, OH. That is, the height measure used in the definition of SI. A model linking these different mean tree heights were developed from the available field sampled tree data using linear regression (Eq. 3).

$$\widehat{\mathrm{H}} = \beta_1 + \beta_2 \mathrm{OH} \quad (3)$$

Estimation of the targeted variables SI and AGE were made using numerical least-squares fitting of the height development model (Eq. 2) to the time series of H estimated from the CHM data via Eq. 3.

The 3D remotely sensed data were analyzed using an area-based approach. Height distributions of the image matched point clouds were summarized by the percentiles corresponding to the 20, 40, 60, 80, 90 and 95 quantiles of the point height distribution at each 10 m field plot. The 95^{th} percentile, p95, was used as the CHM. For TanDEM-X, the CHM was calculated by the mean of the raster cells within each plot. Finally, estimation accuracy was evaluated using the field measured data about forest age and site index.

3. RESULTS AND DISCUSSION

The estimates of H from the CHM data showed reasonable relation to the expected height development (see one example illustrated in Fig. 1). For the DMC data, the numerical least-squares method provided estimates (i.e., converged) for all plots but five. These five plots generally show irregular height developments, possibly caused by disturbance. From the remaining plots, AGE was estimated with an accuracy of 30.3% according to the root mean square error (RMSE) (in percent of the surveyed mean) and SI with 15.9% (Fig. 2). The TanDEM-X data were available in a too short time series to enable reliable estimates of AGE, though. But, solving for SI only (i.e., given the true AGE) provided estimates of SI with an accuracy of 18.6% RMSE from TanDEM-X (Fig. 2). Two plots without convergence were excluded in the latter analysis.

This pilot study shows there are new opportunities available from remote sensing to improving decision making in the modern forestry. Large-scale mapping of forest age and site productivity is clearly possible using CHM data from 3D data. Aerial images are likely to be the most accurate source of data since they are available from the past, in long time series, which capture the slow height development of forest. Other, more accurate, sensors will probably replace aerial images in the future.

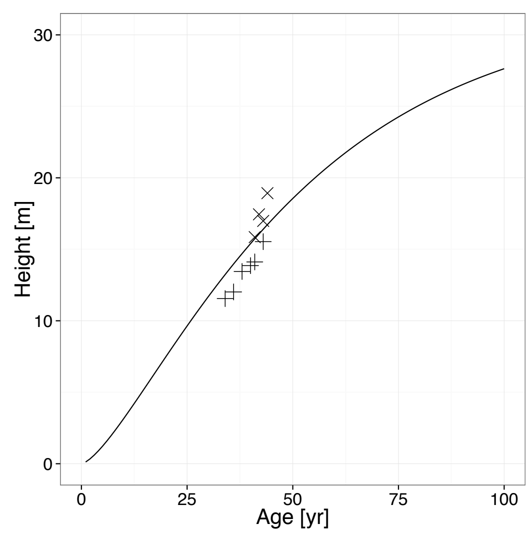

Fig. 1. Data for one of the available field plot - a spruce forest: height development curve (—) corresponding to the measured SI (G30), and estimated H from time series of 3D DMC (+) and TanDEM-X (×) data.

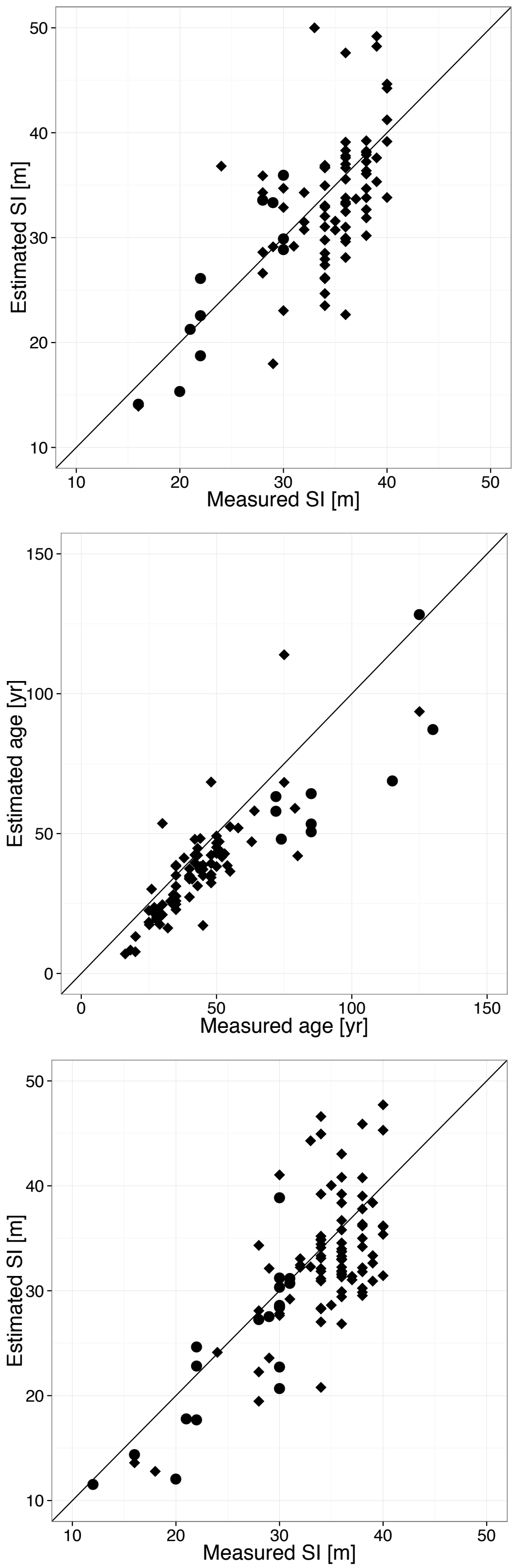

Fig. 2. Estimation results at 10 m radius plots using DMC (top, middle) and TanDEM-X (bottom), with plots dominated by pine (•) or spruce (◆).

4. REFERENCES

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