

## ANALYSIS OF TREE HEIGHT GROWTH WITH TANDEM-X DATA

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### ABSTRACT

Time-series of tree height growth has been estimated from remote sensing data, using TanDEM-X images and airborne laser scanning. The tree height changes detected during three vegetation seasons were fitted to height growth curves in order to estimate the site index, which is a variable related to forest site productivity. This is important ancillary data in forest management planning in order to optimize the values of interest. It was found that the site index could be estimated on 0.5 ha field plots with 12.7% root mean square error (RMSE) using calibrated TanDEM-X data, while the estimations using airborne laser scanning data attained 11.4% RMSE.

### INTRODUCTION

The forest has many different values for many different interest groups, but in Sweden wood production plays a vast role in share of the total amount of available forest. Planning of silvicultural treatments is necessary in order to optimize the wood production and to support this planning, fundamental data about the forest are necessary; for example tree species, stem volume  $\text{ha}^{-1}$ , and age of the forest. It is vital to also have accurate data about the forest site productivity, as it influences the forecasted forest yield. Forest site productivity is defined as the soil's inherent capacity to produce wood volume, i.e. the mean annual production of stem volume  $\text{ha}^{-1}$  for well managed forest growing on the particular site. A commonly used indirect measurement of forest site productivity is the site index (SI). It can be computed in different ways, depending on the forest state (mature forest, clear-cut forest, snow cover and so on) at a certain time point. If no trees are present (e.g., because of altitude or latitude), local soil and vegetation properties can be used, for example soil moisture and field layer vegetation, and the SI is then denoted SIS. This can become a very subjective estimate, highly dependent on the inventorying person, and it is therefore easier to obtain comparable objective data using a different definition, where SI is defined as the average height of the dominant trees  $\text{ha}^{-1}$  at a given reference age (in Sweden commonly the 100 thickest trees at 100 years). In practice, the SI is computed from the age and height measured for the two largest trees within a circular field plot with 10 m radius. In this case, SI is denoted SIH when it is computed from the age and height, and hereafter SI refers to SIH if nothing else stated.

The SI has historically been described from field inventories, and is thus, limited to sample plots representing stands in silvicultural decision plans. Sometimes, it is even expressed at site-level or vaguely expressed for the entire region. The strong reliance on tree height for SI estimation makes it a crucial variable to measure and the chances of succeeding have never been better, as many remote sensing techniques offer ideal platforms for height measurements. Many studies have so far neglected tree height growth – even when the time period studied has covered several years (1), (2). Moreover, remote sensing has provided generally improved and additional decision support data, to a low-cost and with excellent quality, the last couple of years. Common remote sensing techniques (e.g., airborne laser scanning and satellite borne methods) are acquiring data from airborne platforms, which simplifies generation of large area maps of forest properties (e.g., tree height, stem volume and basal area), compared to field based methods.

Data collection from airplanes tend to be repeated only rarely (because of the costs), while the satellite platform offers frequent acquisitions with repetition times of a few weeks. The X-band radar system TanDEM-X has showed to deliver images that can be processed interferometrically with excellent quality, offering a few meters resolution and geolocation on the order of meters (1),

(3)–(5). To compute such forest property maps mentioned earlier, an accurate terrain model (DTM) is required, to describe the ground. This is now available both in Sweden and many other countries.

In the current study, the tree height change was investigated during 3 vegetation seasons, and a method to derive the site index (SI) is suggested. The tree height change was expressed species wise, in terms of SI.

## MATERIAL AND METHODS

### Data

Comprehensive data sets were available for the hemi-boreal forest in Remningstorp (Lat. 58°30' N, Long. 13°40' E), Sweden, between 2011 and 2014. After the vegetation season 2010, an inventory with 40 subjective field plots with 40 m radius was carried out. The locations were chosen such that mature homogenous forest could hold the entire field plots. Trees with diameter at breast height (DBH)  $\geq 0.04$  m were calipered and the height was measured on a sub-sample of about 10% of the trees. These plots were inventoried again in 2014, with the only difference that height was now measured on about 25% of the trees. In total, 25 plots contained unchanged forest during the evaluated time period, consequently, SI could be computed on 25 coniferous (>70% of the stem volume) field plots that were not influenced by forestry actions.

Airborne laser scanning (ALS) data were collected in the fall 2010 (before the first evaluated vegetation season) and in the fall 2014 (after the last evaluated vegetation season), with  $> 10 \text{ m}^{-2}$  point density. Rasters with 5 m pixel size were computed for percentile 99, above a 1.37 m threshold. The DTM utilized was produced by the Swedish National Land Survey (Lantmäteriet) from ALS data, with  $0.5 \text{ m}^{-2}$  point density, and 2 m pixel size (6), (7).

Four TanDEM-X images were acquired in strip-map mode annually from June 2011 until June 2014, with VV-polarization and 135 m to 216 m across-track baselines (suitable for forest mapping (8), Table 1). The images were chosen because of their similar acquisition conditions in terms of baseline, polarization and incidence angle. The first image was acquired in the beginning of the first evaluated vegetation season and the last one in the beginning of the vegetation season 2014.

*Table 1: List of remote sensing data utilized.*

Data source	Date	Across-track baseline [m]	Incidence angle [°]	Polarization
TanDEM-X	2011-06-04	141	41	VV
TanDEM-X	2012-06-01	216	41	VV
TanDEM-X	2013-07-02	135	41	VV
TanDEM-X	2014-06-08	179	41	VV
ALS	2010-08-29	-	-	-
ALS	2014-11-25	-	-	-

### Field data preparation

The SI was computed for the 25 field plots using current tree height growth curves, applicable for Swedish forests, which have been published by Johansson et al. in (9). They are based on difference equations and a special case of Hossfeld's growth functions from 1822 (10). The solution can be presented in its general form as

$$H2 = \frac{(H1+d+r)}{2 + (4 \cdot \beta \cdot A2^{b2}) / (H1-d+r)} \quad (\text{Eq. 1})$$

$$d = \beta \cdot asi^{b2} \quad (\text{Eq. 2})$$

$$r = \sqrt{(H1 - d)^2 + 4 \cdot \beta \cdot H1 \cdot A1^{b2}} \quad (\text{Eq. 3})$$

where  $H1$  and  $A1$  are the measured height and age,  $H2$  the dominant height at the chosen reference age (100 years in Sweden), and  $A2$  is the reference age.  $asi$ ,  $\beta$  and  $b2$  were the parameters estimated species wise in (9).

### Height model generation

Height models were created for each year, both from ALS and from TanDEM-X data. In case of ALS, percentile 99 solely was chosen as explanatory variable; however ALS data were only available at time 0 (before the vegetation season 2011) and time 4 (after the vegetation season 2014). To evaluate tree height growth annually, ALS height data had to be interpolated to get successive heights. This is an estimation that is likely to hold during short time intervals, which here is the case (~3 years).

The TanDEM-X images were processed interferometrically in a traditional way, using the software Gamma (11), to generate height and coherence maps with 5 m pixel size. These were then used to generate height models, using non-linear regression on the form of (Eq. 4) and the parameters where chosen to fit ALS percentile 99 as good as possible (the same parameters were used for the entire test site).

$$p99 = C \cdot H^\alpha \cdot Coh^\beta \quad (\text{Eq. 4})$$

where  $C$  is a scaling constant,  $H$  the interferometric height,  $Coh$  the interferometric coherence, and  $\alpha$  and  $\beta$  are exponent variables to be fitted by the model. Cross-validation on the field plots revealed the root mean square error (RMSE) for the TanDEM-X based height models to be from 11.7% to 13.5%, for the different years.

### SI model fitting

The evaluation of SI from remote sensing data used the following approach (Figure 1).

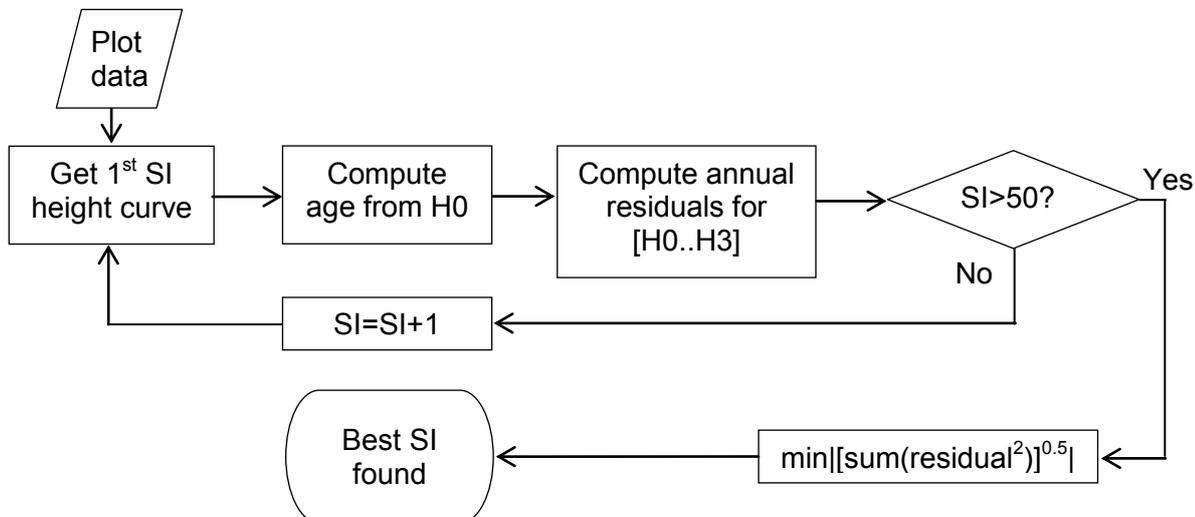


Figure 1: Flow chart of the plot-wise determination of SI from the series of remote sensing based heights (TanDEM-X or ALS data).

The SI was simply estimated by applying a “closest-fit” to published tree height growth curves. In detail, the age was computed out of the first year’s plot mean height (TanDEM-X or ALS based) for respective height curve. Each height curve corresponds to the SI for a specific species. Then the theoretical height growth was computed from the initial height, and compared with the estimated heights attained from TanDEM-X or ALS for the four time points, to compute annual residuals. The estimated SI was found from minimizing the square root of the sum of squared residuals, i.e. the height curve for which the current height development fits the best.

### Accuracy assessment

The main measure for determining the estimation was RMSE, which was expressed as the square root of the average squared errors.

## RESULTS

The overall results showed that the SI could be estimated with 12.7% RMSE (4.6 m), using TanDEM-X based height data that were calibrated against ALS percentile 99. The corresponding result using ALS percentile 99 was 11.4% RMSE (4.1 m). A scatter plot of the TanDEM-X based estimations is shown in Figure 2.

As age estimation is the first step of the residual estimation, this step is crucial for the outcome and a few options were considered. The option used for now lets the first remote sensing image define the initial age, and thereafter the difference compared to the theoretical tree height growth is computed. This has been selected because it led to the lowest RMSE. A different option that was evaluated used the mean height of all four years to estimate the mean age. Then the initial year had to be subtracted by half of the evaluated time period. The thought was, that this should lead to more robust age estimation, however the RMSE turned out to be higher for this particular data set.

Radar data have an inherent instability at pixel level and this probably evolved, as a few plots turned out to have negative height changes between a few single years (Figure 3).

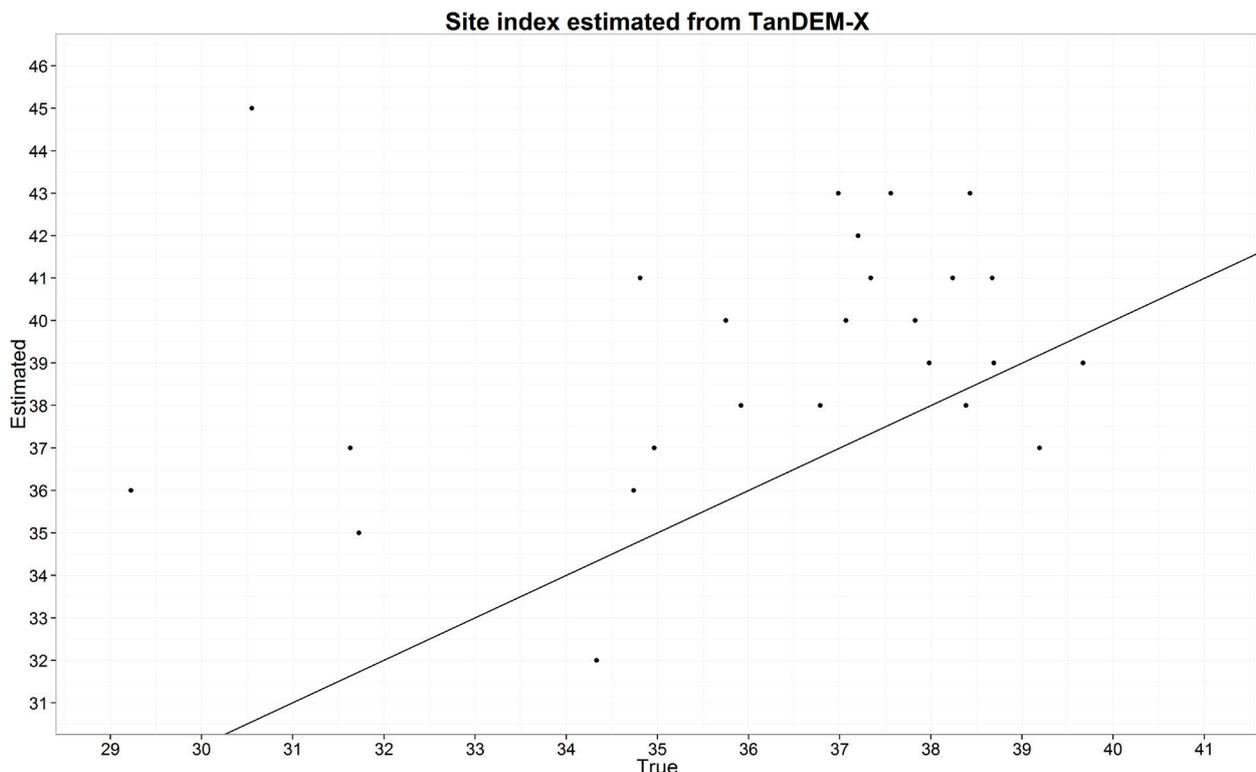


Figure 2: Scatter plot of the site index estimation in coniferous forest based on TanDEM-X data. RMSE=12.7%.

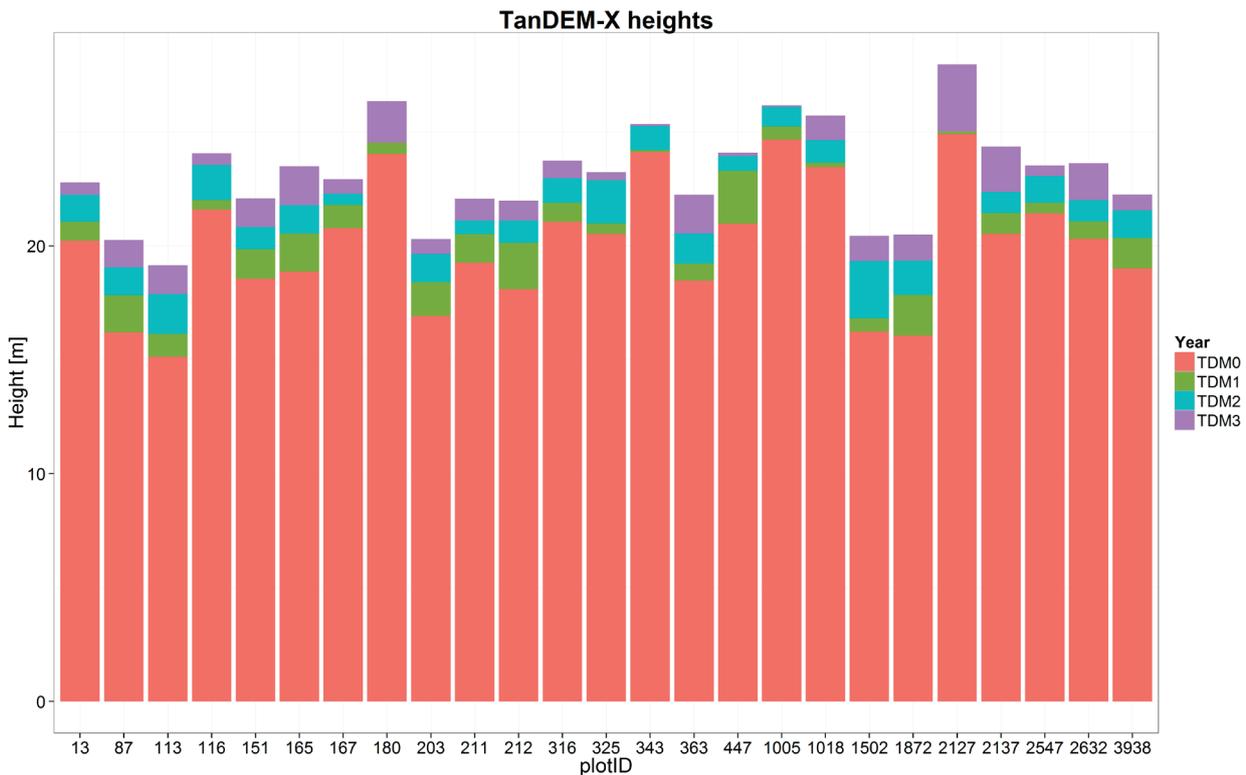


Figure 3: Bar plots of detected height change from TanDEM-X data throughout the years. Years 1-3 show only the additional height growth compared to year 0.

Also, radar data have to be calibrated in order to attain appropriate heights, and for now, this was achieved through ALS data, which it of course should not rely on for an operative circumstance. We definitely see possible approaches also without using ALS as reference data, but this was a first attempt to find out any potential of estimating SI following this method. The accuracy of forest heights derived from radar based processing is currently vastly investigated by different research groups.

This method of estimating SI from a very short (in this time perspective) time period requires current height changes to be similar to those that have characterized the trees development for maybe the last fifty years, which might not be true. However, this study shows that the similarities are great enough to increase earlier silvicultural decision basis.

The estimation accuracy obtained from ALS based data was similar to TanDEM-X based, and the question is rather why ALS based data should be used for this purpose, as frequent remote sensing data are easier and cheaper to acquire from the satellite platform. It is not clarified whether the difference in RMSE between ALS and TanDEM-X based estimations depend on the slightly different measures of time periods or of the inherent differences in obtained data. The potential is obvious, of using lots of sequential radar data each year. Nevertheless, there still does not exist a perfect model of how estimated tree heights could be corrected because of the natural yearly fluctuations (e.g., because of freezing/thawing or leaf-on/off).

A linear interpolation between the ALS acquisitions was used because of the short time period for ALS based data. More correct, should probably be to only find the best fit along all SI curves.

In this study, the TanDEM-X data were used to calibrate a height model related to ALS percentile 99, while site index relates to the dominant trees. Therefore, an improved approach should first calibrate the TanDEM-X data to basal area-weighted heights (Lorey's height).

## CONCLUSIONS

This study shows the potential of developing large wall-to-wall maps of site index, which is an additional variable, important for among others, forest management planning. The site index could be estimated from remote sensing data extending three vegetation seasons. TanDEM-X data were acquired at four time points, from which the estimation accuracy was 12.7%, while ALS data were acquired at two time points (before and after the three vegetation seasons), and the corresponding RMSE was 11.4%. The presented approach requires a DTM and knowledge about the tree species composition to be used correctly. Furthermore, the required time span to accurately estimate the SI should be further evaluated as well as the use of height estimations at different moments within the same year.

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