



This is an author produced version of a paper published in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing.

This paper has been peer-reviewed but may not include the final publisher proof-corrections or pagination.

Citation for the published paper:

Persson, Henrik and Fransson, Johan. (2016) Estimating site index from short term TanDEM-X canopy height models. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*. Volume: 9, Number: 8, pp 3598-3606.

<http://dx.doi.org/10.1109/JSTARS.2016.2563158>.

Access to the published version may require journal subscription.

Published with permission from: Institute of Electrical and Electronics Engineers (IEEE).

Standard set statement from the publisher:

“© 2016 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.”

Epsilon Open Archive <http://epsilon.slu.se>

ESTIMATING SITE INDEX FROM SHORT TERM TANDEM-X CANOPY HEIGHT MODELS

Henrik J. Persson* and Johan E.S. Fransson

Department of Forest Resource Management, Swedish University of Agricultural Sciences,
SE-901 83 Umeå, Sweden; E-Mail: johan.fransson@slu.se

*Author to whom correspondence should be addressed; E-Mail: henrik.persson@slu.se

Tel.: +46-90-786-8105.

Keywords: Site Index, Growth, TanDEM-X, InSAR, Height, ALS, DEM, SAR

ABSTRACT

The tree height growth from 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. The tree height growth was evaluated for four different cases, in which remote sensing data from TanDEM-X and airborne laser scanning were evaluated. The evaluated method requires a digital terrain model and knowledge about the tree species. Furthermore, the remote sensing data were calibrated using Lorey's heights or airborne laser scanning data.

It was found that four annual acquisitions of calibrated TanDEM-X data covering three vegetation seasons could be used for estimating the site index on twenty-seven 0.5 ha field plots with 4.4 m (12.1%) RMSE. The site index could in a similar manner be estimated from only two airborne laser scanning acquisitions, before and after four vegetation seasons, with 2.3 m (6.3%) RMSE.

I. 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 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 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 (e.g., mature forest or clear-cut forest) at a certain time point [1], [2]. If no trees are present (e.g., because of a clear-cut), local soil and vegetation properties can be used, for example soil moisture and field layer vegetation, and the SI is then denoted SIS [3]. 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 ha^{-1} at a given reference age (in Sweden commonly the 100 thickest trees at 100 years). The SI can then in practice be 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.

There are some studies which show the potential of using the remote sensing techniques airborne laser scanning (ALS) [4]–[6] or airborne photographs [7] in order to estimate the SI. However, they often require the stand age to be known or several (expensive) ALS acquisitions. In 2008, Vége and St-Onge presented a method for mapping the site index from long term aerial photographs [7]. They

evaluated different combinations of four acquisitions of scanned aerial photographs between 1945 and 2003 to create time series of canopy height models, from which they derived the SI. They used a test site which burned in 1923 which established even age, homogenous forest, in which they chose solitary single-species forest (jack pine). They found that aerial photographs could be used to quantify both SI and stand age, with an average bias of 0.76 m (2.41 m RMSE) and 1.86 years (7 years RMSE). Tompalski et al. (2015), presented a method for combining time series of Landsat imagery to attain the age, and in addition to this only one acquisition of height – acquired from ALS – was needed, in order to estimate the SI for young forest [8]. Their approach led to 5.55 m RMSE and 0.70 m bias.

Swedish forests grow rather slow in an international context and optical satellite images are rarely available from the time when the forest last time was clear-cut. Nevertheless, satellite data have some excellent advantages because of its availability, coverage and cheap acquisitions. The X-band radar system TanDEM-X has showed to deliver images that can be processed interferometrically with good quality, offering a couple of meters resolution and geolocation on the order of meters [9]–[14]. The interferometric phase as well as the coherence contain important information for tree height and biomass estimations [15]–[18].

To compute canopy height models from satellite data, an accurate digital terrain model (DTM) is required, to describe the ground. This is now available in Sweden as well as in many other countries.

The authors of the current paper presented preliminary results, where TanDEM-X data were calibrated against ALS percentile 99 (p99) elevation data [19]. In this study, the same data set has been further evaluated and extended.

The main hypothesis tested in this study is that the site index can be estimated for mature homogenous coniferous forest from very short time-series (three vegetation seasons) of the forest height by using satellite X-band radar data, in this case TanDEM-X, when an accurate terrain model is

available. This is the first study known to the authors, where short-term satellite radar data solely are used for SI estimations. The tree height change was expressed species wise, in terms of SI.

II. STUDY AREA AND DATA

Several data sets were available for the hemi-boreal forest in Remningstorp (Lat. 58°30' N, Long. 13°40' E), Sweden, between 2011 and 2014 (Figure 1). After the vegetation season 2010, an inventory with 32 field plots with 40 m radius was carried out. The locations were chosen such that mature homogenous forest could encompass the entire field plots. Trees with diameter at breast height (DBH) ≥ 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, 27 plots contained unchanged (no forestry actions or extensive injuries) forest during the evaluated time period. On the unchanged plots, the two largest trees within 10 m from the plot center were calipered and drilled at breast height, and consequently, SI could be computed on 27 coniferous field plots that were not influenced by forestry actions (Figure 2). Four of the plots were pine dominated and the remaining ones spruce. The inventoried age and SI distribution for the plots are presented in Figure 3.

In addition to the 40 m plots, there were 10 m plots available, which were inventoried late 2010 and again in 2014. Out of the data set of about 200 systematically distributed plots, only unchanged plots (during the investigated time period), with known species and site index were chosen, which made 75 plots with 10 m radius available for calibration purposes.

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 (Table 1). Rasters with 5 m pixel size were computed for percentiles p99 and p60, above a 1.37 m threshold. The DTM utilized was produced by the Swedish National Land Survey (Lantmäteriet) from ALS data, with 0.5 m^{-2} point density, and 2 m pixel size [20], [21] .

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 [22], Table 2). 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. The 2013 acquisition was acquired slightly later than the others, though still in the middle of the vegetation season. However, the biggest part of height growth takes place during May, June and July in this region, which might cause a smaller detected height growth between 2013 and 2014, and conversely a slightly larger growth between 2012 and 2013.

III. METHODS

A. Field data preparation

The SI was computed for the 27 field plots (Figure 2) using established tree height growth curves, applicable for Swedish forests, which have been published by Johansson et al. in [23]. They are based on difference equations and a special case of Hossfeld's growth functions from 1822 [24]. 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 total age, $H2$ is the dominant height at the chosen reference age (100 years in Sweden), and $A2$ is the reference age. asi , β and $b2$ are the parameters estimated species wise [23].

Based on these formulas, species wise growth curves can be plotted as in Figure 4.

B. Canopy height model generation

Canopy height models were created for each year, both from ALS and from TanDEM-X data. In all cases, ALS data were used for creating the DTM. Four different cases were investigated, where the following data sources were used for estimating the SI.

1. TanDEM-X height data were calibrated against field sampled Lorey's mean height.
2. TanDEM-X height data were calibrated against ALS p99 (used as "true" height).
3. ALS data with p99 and p60 were used to first estimate Lorey's mean height, from which the estimated heights then were used to estimate the SI [25], [26].
4. ALS p99 was solely used as input for the SI estimation.

The TanDEM-X images were processed interferometrically in a traditional way, using the software Gamma [27], [28], to generate interferometric height and coherence maps with 5 m pixel size. The SLCs were already co-registered, hence the following steps were interferogram generation (including common spectral band filtering), 3x3 pixels multilooking, removal of flat Earth phase trend and removal of the additional topographic phase trend (computed from ALS data). Hereafter, estimation of interferometric correlation, phase unwrapping using a branch cut algorithm, and finally generation and interpolation of topographic height and coherence maps were accomplished [29], [30]. The maps were geocoded by using a look-up table (LUT), which was computed for the coordinate transformation between the range-Doppler coordinates (RDCs) and orthonormal map coordinates. The initial LUT transformation was calculated based on the orbital data and ancillary SAR image information, but was improved by an iterative process where the ellipsoidal DTM was matched against a multilooked TanDEM-X intensity image, by using cross-correlation analysis.

The geocoded height and coherence maps were used to generate height models (negative heights were filtered out), using non-linear regression on the form of (Eq. 4) and the parameters were chosen to fit either Lorey's mean height or ALS p99 for the 75 plots with 10 m radius as good as

possible (the same parameters were used for the entire test site). This is the calibration mentioned in the cases 1 and 2 above. As illustration for case 2 above, the relation looked like:

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

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

For case 3, multiple linear regression was used and for case 4 where solely $p99$ was used, no training plots were needed. The parameter values for α , β and C are presented in Table 3 and the resulting RMSEs of the calibrations are presented in Table 4.

In the process of estimating SI (described in the next section), the initial estimated height value is crucial (or correspondingly the age), and therefore the calibration of TanDEM-X data against some reference data was necessary, as a clear penetration also from X-band radar is known [9], [18], [31]. The calibration was made against Lorey's mean height, since it is commonly used in the Swedish forest industry and it is also simply attained from computations of the normally sampled metrics DBH and height. However, neither Lorey's mean height, nor the other reference metrics, is the same metric as the dominant height which is used in the definition of SI. Therefore, an error (bias) is expected, and the results are also presented with and without bias correction.

ALS data were only available at time 0 (before the vegetation season 2011) and time 4 (after the vegetation season 2014). This explains the empty columns in Table 4 for 2012 and 2013. To evaluate tree height growth annually, ALS height data had to be interpolated to get successive heights and to give the residual computation the same conditions as with TanDEM-X data. The linear assumption is likely to hold during short time intervals, which here is the case (about three years).

C. SI model fitting

The procedure for determining the SI from the remote sensing height models used the following approach (Figures 5 and 6). The SI was simply estimated by applying a "closest-fit" of remote sensing

heights to published tree height growth curves. The following steps were carried out for each SI curve.

1. Determine the initial age and height from the remote sensing height data. The initial age was computed from the age/height relation for each height growth curve (giving different ages for each curve). This was done, by first averaging all four height measurements (also for interpolated ALS based height models, in order to avoid different residual accumulations), from which the middle age was obtained, and then the initial age could be computed by subtracting half of the evaluated time period (1.5 years). Each height curve corresponds to the SI for a specific species.
2. Compute annual residuals. The theoretical height growth during the evaluated three years period 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.
3. Find the best SI curve. The best SI estimation 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.

The main measure for determining the estimation quality was RMSE, which was expressed as the square root of the average squared residuals. The bias was computed as the mean of the differences between the estimated and true SI values, and the RMSE is therefore presented both with and without bias corrected SI values. In addition, the Pearson correlation coefficient r was computed.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The results are presented in Table 5 with and without bias correction, as an obvious bias could be noticed in the models, probably stemming from the bias in field measured age (measured at breast height, while the computation of SI curves require total age), and possibly also from the slightly inaccurate height models attained. The corresponding scatter plots for the four bias corrected cases

are presented in Figures 7 a-c, e, and one un-corrected scatter plot for case 4 is presented in Figure 7d. The Figures 7b and 7e are most important, as they represent the products applicable in forestry.

The results showed that the SI could be estimated rather accurate, considering the short time period. By using only two time points, ALS p99 (case 4, Table 5) was the best estimator of SI, when bias corrected RMSE was concerned (2.3 m, 6.3%, $r=0.61$). Considering the space-borne alternative with TanDEM-X data, the RMSE was about twice as high with 4.4 m, 12.1%, and $r=0.32$ (Table 5), but still usable considering that only three vegetation seasons was concerned to describe the past maybe 50 to 80 years of tree growth. The strongest correlation $r=0.70$ between the estimated SI and the reference SI, was found for the bias-corrected TanDEM-X that were calibrated against ALS p99 (case 2). The RMSEs between two and six meters for cases 1, 2 and 4 are well in line with the results by [4] and [5], despite the considerably shorter time series used in the current study. The relative RMSEs appear rather low, partly as a result of the true site indexes being rather high (29 to 40 m, Figures 7a to 7e).

A bias was noticed in all four cases. A large part can likely be originating from the difference in how the field measured age and height were used in the site index models. The tree height growth curves described in [23] (which were used also for this study) expect the total age and height as input and in the current study, only age at breast-height together with total height were available. No attempt was made to compensate for the bias caused by this difference, as this would be difficult to model, and it would also introduce additional uncertainties. Instead the results are presented with and without bias correction. This should be further considered in future studies.

The bias noticed in the cases 2, 3 and 4 which relates to ALS data (Table 5), are larger than in [4] and [5] (0.76 m and 0.70 m). This might partly be explained by the case, that the ALS acquisition 2014 was obtained in the fall 2014, which is clearly after the vegetation season. The TanDEM-X acquisition was acquired June 8, 2014, which is in the beginning of the growing season, and therefore the ALS

acquisition is actually measuring almost an entire vegetation season more, despite it was handled in the same way as all data.

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 chosen (described in Section III.C) uses all measurements to create a robust estimation of the height, and therefore making the method less vulnerable against poor first year image data, which would be a different option: to let the first remote sensing image solely define the initial age, and thereafter the difference compared to the theoretical tree height growth is computed. It was shown in [19] that this could lead to a lower RMSE, however, this might be dependent only on the specific dataset evaluated.

The estimated age residuals are generally larger for older trees (Table 6), which likely depends on the much smaller difference in expected height change for three succeeding years, as the height curves flattens over time (Figure 4). Moreover, all age estimations contain large errors, also from ALS data, especially at ages > 60 years. For Case 1, where TanDEM-X data were calibrated against Lorey's height, the RMSE for age was 17.8 years and for Case 3, where ALS p99 were calibrated against Lorey's height, the RMSE was 18.0 years. Better data about the tree age could greatly improve the SI estimations.

The SI computed from the field data were used as estimations for the SI for the entire 40 m plots. According to the definition, the two dominant trees are used for a 10 m radius plot, and correspondingly more trees should be measured for larger plots. However, such measurements were not available and past experience from the test region pointed towards that the SI should not vary too much within the relatively homogenous plots.

Radar data have an inherent instability at pixel level (speckle) and this probably evolved, as a few plots turned out to have slightly negative height changes between a few single years (Figure 8).

Radar data also have to be calibrated in order to attain appropriate heights, and in this study this

calibration was tested both against field sampled height data and ALS data, which preferably would not be necessary for an operative circumstance. Estimation methods and accuracy evaluation of forest heights derived from radar based processing is currently vastly investigated by different research groups. It was noticed, that several plots with the largest residual SI values contained the tallest forest and they were located in slopes without buffer to neighboring clear-cuts during the investigated time period. Two of the TanDEM-X acquisitions possessed height-of-ambiguities between 32 m and 38 m, which seemed to cause some unwrapping problems at pixel level. This was tried to be taken care of during the interferometric processing, but nevertheless, the evaluated method might be sensitive to the local site conditions.

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. Better data about the tree age would likely improve the SI estimations. However, this study shows that the similarities are large enough to gain increased value of the current decision basis for planning forest management. The potential to estimate SI is understandable from the use of vast sequential radar data available 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).

In this study, the TanDEM-X data were used to calibrate the height models to Lorey's height or ALS p99, while site index relates to the dominant trees. Therefore, an improved approach should focus on skipping the demand of calibration, and instead consider both radar penetration and the different reasons for bias, to attain an improved model for estimating the SI.

SUMMARY AND CONCLUSIONS

This study shows the potential of using radar for developing large wall-to-wall maps of site index, which is an additional variable, important for among others, forest management planning. The site

index was estimated from remote sensing data extending three vegetation seasons at 27 field inventoried plots with 40 m radius. Four acquisitions of TanDEM-X data covering three vegetation seasons were calibrated against Lorey's mean height. The height growth extracted from the canopy height models were fitted to height growth curves to find the site index. The estimation accuracy in terms of RMSE using TanDEM-X data was 4.4 m, 12.1%, while solely ALS p99 data were acquired at two time points (before and after the three vegetation seasons), and the corresponding RMSE was 2.3 m, 6.3%. 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.

ACKNOWLEDGEMENTS

This study was financed by the Swedish National Space Board through the project "Retrieval of forest biomass and biomass change with spaceborne SAR", contract No. 147/14 and by the Hildur and Sven Wingquist's foundation. It has also received funding from the European Community's Seventh Framework Programme (FP7/2007–2013) under grant agreement No. 606971, the Advanced_SAR project. The authors would like to thank the German Aerospace Center (DLR) for the TanDEM-X data. Finally, the authors would like to thank the reviewers for valuable comments.

REFERENCES

- [1] B. Hägglund and J.-E. Lundmark, *Handledning i bonitering med Skogshögskolans boniteringssystem*. Jönköping: Skogsstyrelsen, 1999.
- [2] B. Hägglund and J.-E. Lundmark, *Fälthäfte i Bonitering Västerbottens län*. Jönköping: Skogsstyrelsen, 1985.
- [3] B. Hägglund and J.-E. Lundmark, "Site index estimation by means of site properties of Scots pine and Norway spruce in Sweden.," 1977.
- [4] D. Gatzliolis, "Lidar-derived site index in the U.S. Pacific northwest - challenges and opportunities," in *ISPRS Workshop on Laser Scanning 2007 and SilviLaser 2007*, 2007, pp. 136–143.
- [5] M. Holopainen, M. Vastaranta, R. Haapanen, X. Yu, H. Kaartinen, R. Viitala, and H. Hyypä, "Site-type estimation using airborne laser scanning and stand register data," *Photogramm. J. Finl.*, vol. 22, no. 1, pp. 16–32, 2010.
- [6] X. Yu, J. Hyypä, H. Kaartinen, H. Hyypä, M. Maltamo, and P. Rönholm, "Measuring the growth of individual trees using multi-temporal airborne laser scanning point clouds," in *ISPRS Workshop Laser scanning 2005*, 2005, no. 3,4,5, pp. 204–208.
- [7] C. Véga and B. St-Onge, "Mapping site index and age by linking a time series of canopy height models with growth curves," *For. Ecol. Manage.*, vol. 257, no. 3, pp. 951–959, 2009.
- [8] P. Tompalski, N. C. Coops, J. C. White, M. a. Wulder, and P. D. Pickell, "Estimating forest site productivity using airborne laser scanning data and Landsat time series," *Can. J. Remote Sens.*, vol. (in press), no. September, 2015.
- [9] M. J. Soja, H. J. Persson, and L. M. H. Ulander, "Estimation of forest height and canopy density from a single InSAR correlation coefficient," *IEEE Geosci. Remote Sens. Lett.*, vol. 12, no. 3, pp. 646–650, 2015.
- [10] H. Persson and J. E. S. Fransson, "Forest Variable Estimation Using Radargrammetric Processing of TerraSAR-X Images in Boreal Forests," *Remote Sens.*, vol. 6, no. 3, pp. 2084–2107, Mar. 2014.
- [11] F. Kugler, S. Lee, I. Hajnsek, and K. P. Papathanassiou, "Forest Height Estimation by Means of Pol-InSAR Data Inversion : The Role of the Vertical Wavenumber," *IEEE Trans. Geosci. Remote Sens.*, vol. 53, no. 10, pp. 5294–5311, 2015.
- [12] T. P. Ager and P. C. Bresnahan, "Geometric precision in space radar imaging: results from TerraSAR-X," in *ASPRS 2009 Annual Conference*, 2009, p. 8.
- [13] J. Praks, O. Antropov, and M. T. Hallikainen, "LIDAR-Aided SAR interferometry studies in boreal forest: scattering phase center and extinction coefficient at X-and L-band," *IEEE Trans. Geosci. Remote Sens.*, vol. 50, no. 10, pp. 3831–3843, 2012.
- [14] S. Solberg, R. Astrup, J. Breidenbach, B. Nilsen, and D. Weydahl, "Monitoring spruce volume and biomass with InSAR data from TanDEM-X," *Remote Sens. Environ.*, vol. 139, pp. 60–67, Dec. 2013.
- [15] M. Schlund, F. von Poncet, S. Kuntz, C. Schmullius, and D. H. Hoekman, "TanDEM-X data for aboveground biomass retrieval in a tropical peat swamp forest," *Remote Sens. Environ.*, vol. 158, no. March 2016, pp. 255–266, 2015.
- [16] F. Kugler, D. Schulze, I. Hajnsek, H. Pretzsch, and K. P. Papathanassiou, "TanDEM-X Pol-InSAR performance for forest height estimation," *IEEE Trans. Geosci. Remote Sens.*, vol. 52, no. 10, pp. 6404–6422, 2014.

- [17] A. T. Caicoya, F. Kugler, I. Hajsek, and K. Papathanassiou, "Boreal forest biomass classification with TanDEM-X," in *In Proceedings of IEEE International Geoscience and Remote Sensing Symposium*, 2012, pp. 10–13.
- [18] H. J. Persson, "Estimation of Forest Parameters Using 3D Satellite Data," Swedish University of Agricultural Sciences, 2014.
- [19] H. J. Persson and J. E. S. Fransson, "Analysis of tree height growth with TanDEM-X data," in *35th EARSeL Symposium*, 2015, no. 1, pp. 1–6.
- [20] Lantmäteriet, "Kartografisk information ur laserdata," 2011.
- [21] H. Bergström, H. Melin, and A. Nicolausson, "Höjddata – en förutsättning för klimatanpassning," Swedish National Land Survey, Gävle, Sweden, 2009.
- [22] M. J. Soja and L. M. H. Ulander, "Digital Canopy Model Estimation from TanDEM-X Interferometry Using High-resolution Lidar DEM," in *In Proceedings of IEEE International Geoscience and Remote Sensing Symposium*, 2013, pp. 165–168.
- [23] U. Johansson, P. M. Ekö, B. Elfving, T. Johansson, and U. Nilsson, "Nya höjddatautvecklingskurvor för bonitering," *issue 14, Fakta Skog - Rön från Sveriges lantbruksuniversitet*, p. 6, 2013.
- [24] C. J. Cieszewski and I. E. Bella, "Polymorphic height and site index curves for lodgepole pine in Alberta," *Can. J. For. Res.*, vol. 19, pp. 1151–1160, 1989.
- [25] E. Næsset, T. Gobakken, J. Holmgren, H. Hyyppä, J. Hyyppä, M. Maltamo, M. Nilsson, H. Olsson, Å. Persson, and U. Söderman, "Laser scanning of forest resources: The nordic experience," *Scand. J. For. Res.*, vol. 19, no. 6, pp. 482–499, 2004.
- [26] J. Holmgren, "Prediction of tree height, basal area and stem volume in forest stands using airborne laser scanning," *Scand. J. For. Res.*, vol. 19, no. 6, pp. 543–553, Dec. 2004.
- [27] Gamma, "Gamma Remote Sensing Consulting AG Software." [Online]. Available: <http://www.gamma-rs.ch/>.
- [28] U. Wegmüller, C. Werner, and T. Strozzi, "SAR interferometric and differential interferometric processing chain," *Proc. IGARSS'98*, pp. 1106–1108, 1998.
- [29] U. Wegmüller, C. L. Werner, T. Strozzi, and A. Wiesmann, "Phase Unwrapping with GAMMA ISP Technical Report, 13-May-2002," Gamma Remote Sensing, Bern, Switzerland, 2002.
- [30] M. Costantini, "A novel phase unwrapping method based on network programming," *IEEE Trans. Geosci. Remote Sens.*, vol. 36, no. 3, pp. 813–821, 1998.
- [31] R. Perko, H. Raggam, J. Deutscher, K. Gutjahr, and M. Schardt, "Forest assessment using high resolution SAR data in X-band," *Remote Sens.*, pp. 792–815, 2011.



Henrik J. Persson received his M.Sc. degree in engineering physics from Luleå University of Technology in 2009 and the Ph.D. degree in forest remote sensing from the Swedish University of Agricultural Sciences (SLU), Umeå, Sweden, in 2014. From 2009 to 2011 he worked at the Swiss Federal Institute of Technology (ETH), Zürich, Switzerland. He is now within the forest remote sensing group at SLU with his main research focusing on forest parameter modeling from radar and optical sensors obtained from satellites, and airborne laser scanning data.



Johan E. S. Fransson (SM'12) was born in Karlshamn, Sweden, in 1967. He received the M.Sc. in forestry and Ph.D. in forestry remote sensing from the Swedish University of Agricultural Sciences (SLU), Umeå, Sweden, in 1992 and 1999, respectively. Since 1993, he has been with the Department of Forest Resource Management, SLU, Umeå. In 2000 and 2002 he was appointed as Assistant Professor and Associate Professor in forestry remote sensing, respectively. He became the Head of the Department in 2008. His main research interest concerns analysis of SAR images for forestry applications. Dr. Fransson received the International Space University Certificate from the Royal Institute of Technology in Stockholm, Sweden, in 1995 and the award from “Kungliga Skytteanska samfundet” to a younger researcher at SLU, Umeå, in 2002.

TABLES

Table 1. List of ALS data utilized.

Data source	Date	Wavelength	Point density	Pulse Repetition Frequency
TopEye MkIII (S/N700)	2010-08-29	1550 nm	>10 returns m ⁻²	160 kHz
Riegl LMS-Q680i	2014-11-25	1550 nm	>100 returns m ⁻²	266 kHz

Table 2. List of satellite radar data utilized.

Data source	Date	Across-track baseline [m]	Incidence angle [°]	Polarization	Precipitation [mm]
TanDEM-X	2011-06-04	141	41	VV	0
TanDEM-X	2012-06-01	216	41	VV	11.0
TanDEM-X	2013-07-02	135	41	VV	0
TanDEM-X	2014-06-08	179	41	VV	0

Table 3. Parameter values C , α and β for the generated CHM rasters.

Height model	Reference	2011	2012	2013	2014
		C, α, β	C, α, β	C, α, β	C, α, β
1	H _{Lorey}	5.36, 0.44, -	5.97, 0.42, -	6.89, 0.37, -	9.17, 0.31, -
		0.30	0.11	0.24	0.13
2	ALS p99	4.79, 0.47, -	6.51, 0.38, -	7.01, 0.37, -	8.98, 0.31, -
		0.37	0.12	0.28	0.12

Table 4. Relative RMSE from cross-validation on 75 plots with 10 m radius for the investigated cases in this study.

Case	Calibration	2011	2012	2013	2014
1	TanDEM-X vs. H _{Lorey}	12.4%	10.7%	10.1%	9.7%
2	TanDEM-X vs. p99	11.1%	12.8%	10.9%	11.4%
3	ALS vs. H _{Lorey}	8.4%	-	-	5.5%
4	ALS p99 vs -	-	-	-	-

Table 5. Results from site index estimation with and without bias correction.

Case	Calibration	No bias correction			Bias corrected		
		RMSE (m)	RMSE (%)	Bias (m)	RMSE (m)	RMSE (%)	<i>r</i>
1	TanDEM-X vs. H_{Lorey}	4.7	12.8	1.6	4.4	12.1	0.32
2	TanDEM-X vs. p99	9.6	26.6	7.8	5.6	15.5	0.70
3	ALS vs. H_{Lorey}	11.9	32.9	11.4	10.4	28.7	-0.25
4	ALS p99 vs -	9.2	25.4	8.9	2.3	6.3	0.61

Table 6. Ages measured from field vs. estimated from two remote sensing cases (best options for respective sensor).

	Age (years)	Case 1: TanDEM-X vs. H_{Lorey} (bias corrected for height)		Case 3: ALS vs. H_{Lorey} (bias corrected for height)	
Plot	Field measured (years)	Estimated (years)	Residual (years)	Estimated (years)	Residual (years)
1	44.5	34.0	10.5	40.1	4.4
2	34.5	27.9	6.6	36.2	-1.7
3	30.0	16.0	14.0	28.0	2.0
4	55.0	29.0	26.0	41.1	13.9
5	42.5	21.8	20.7	29.9	12.6
6	52.0	72.4	-20.4	55.9	-3.9
7	88.0	43.8	44.2	34.6	53.4
8	30.0	21.6	8.4	27.0	3.0
9	92.5	48.6	43.9	47.6	44.9
10	36.0	25.9	10.1	37.6	-1.6
11	35.5	20.4	15.1	36.8	-1.3

12	40.0	30.5	9.5	34.4	5.6
13	38.0	27.6	10.4	35.1	2.9
14	84.5	57.9	26.6	54.1	30.4
15	35.0	41.0	-6.0	33.7	1.3
16	43.5	36.5	7.0	44.5	-1.0
17	67.5	46.0	21.5	37.7	29.8
18	47.0	53.9	-6.9	41.8	5.2
19	32.5	20.5	12.0	31.9	0.6
20	30.0	16.2	13.8	31.7	-1.7
21	63.0	63.3	-0.3	36.1	26.9
22	37.5	40.5	-3.0	39.6	-2.1
23	51.0	41.3	9.7	38.4	12.6
24	42.5	53.3	-10.8	35.6	6.9
25	52.0	44.1	7.9	- no data	- no data
26	47.5	37.3	10.2	- no data	- no data
27	36.0	24.1	11.9	34.0	2.0

FIGURES

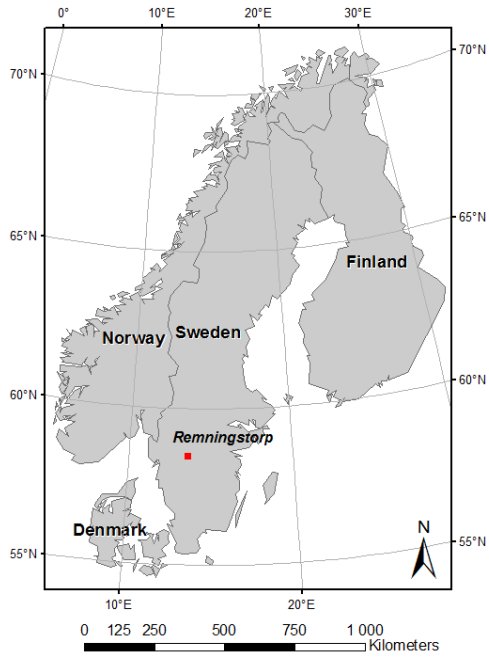


Figure 1. The test site is located in southern Sweden, 58°30' N, 13°40' E, and contains hemi-boreal forest.

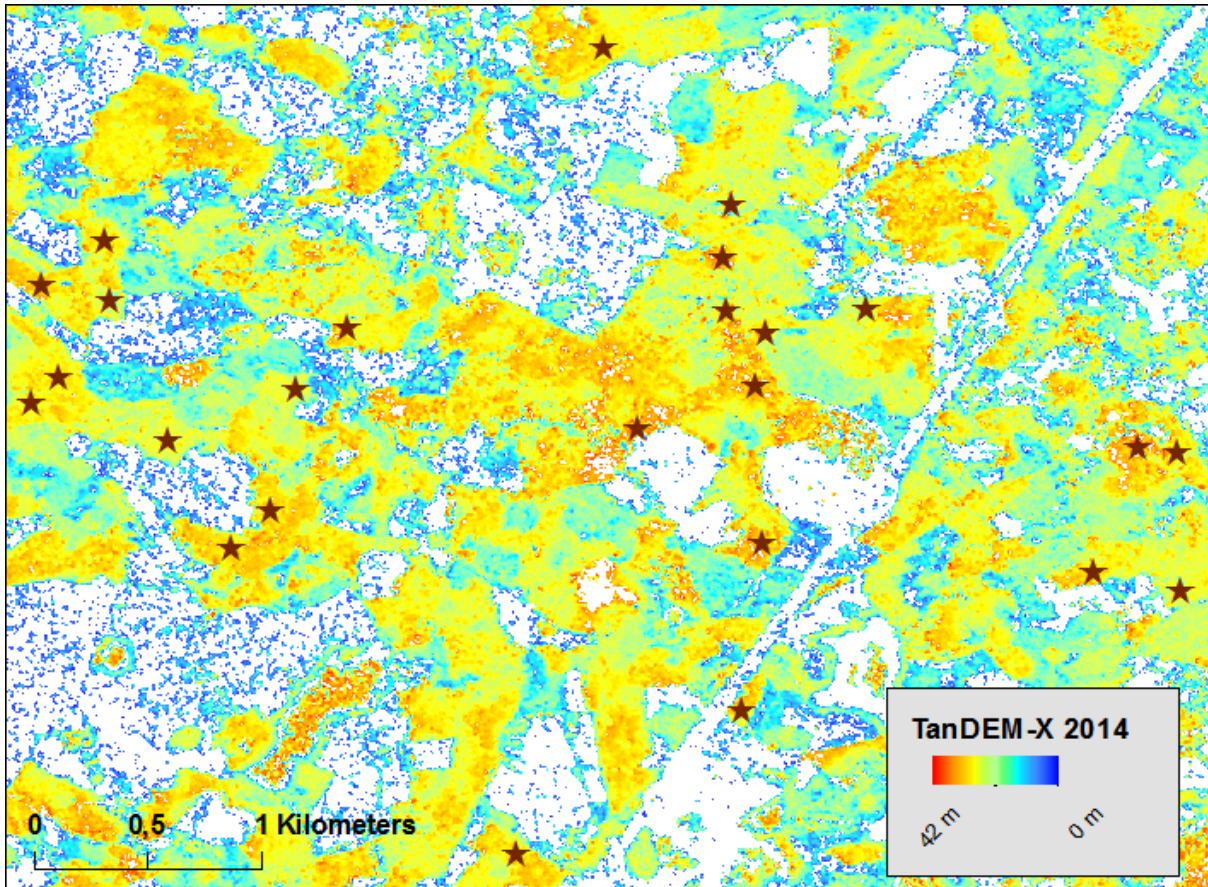


Figure 2. TanDEM-X height map, after calibration against Lorey's height. The 27 evaluation plots are marked with stars.

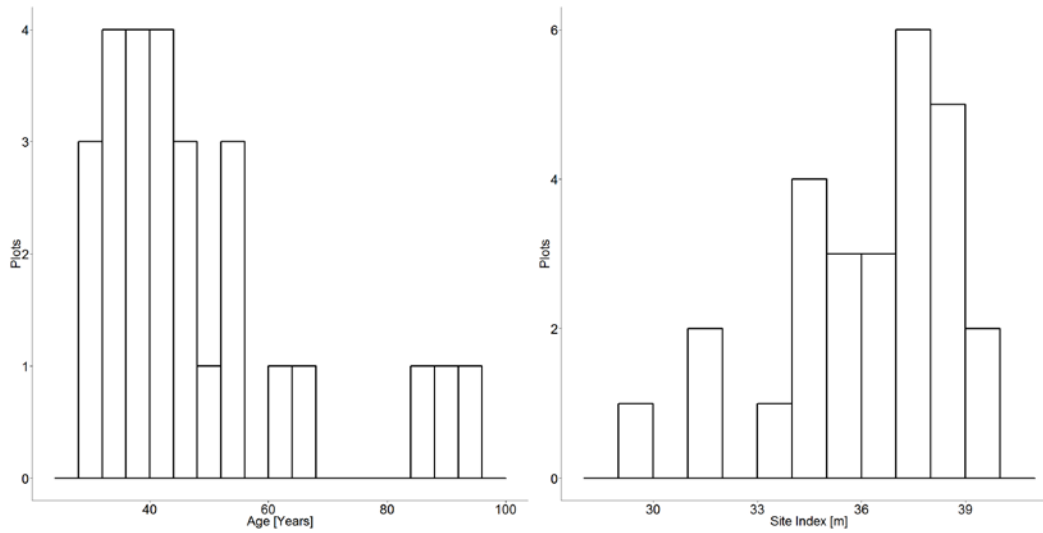


Figure 3. Left: Age distribution of the plots. Right: Site Index-distribution of the plots.

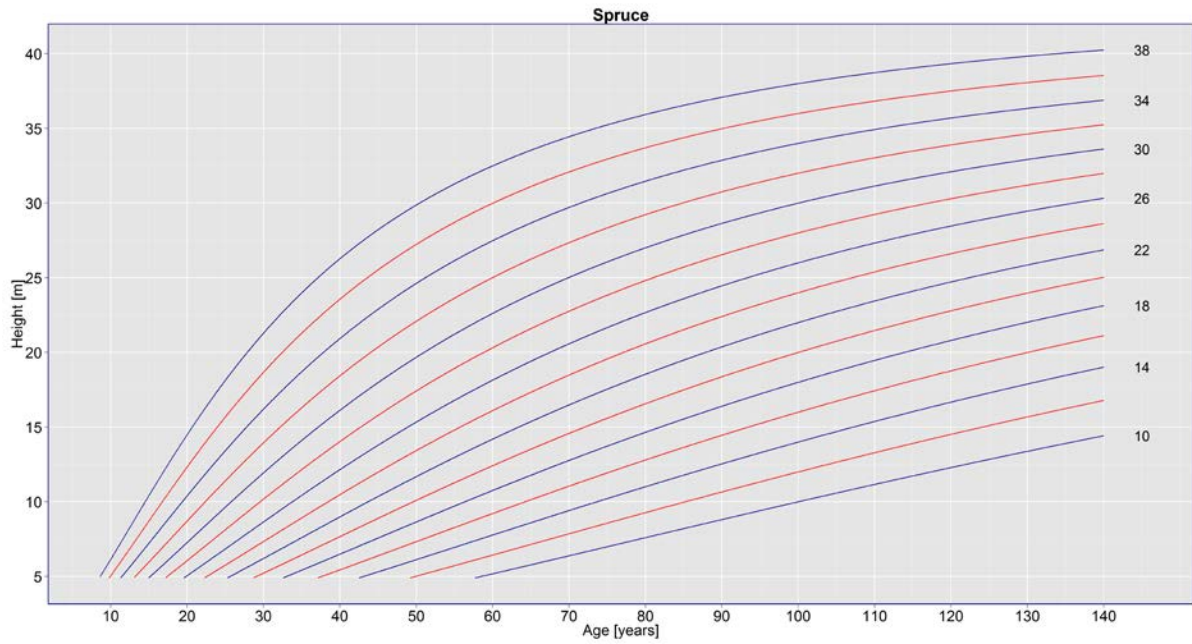


Figure 4. Site index curves for Norway Spruce in Swedish forests, according to Johansson et. al [23]. Each curve represents a different site index.

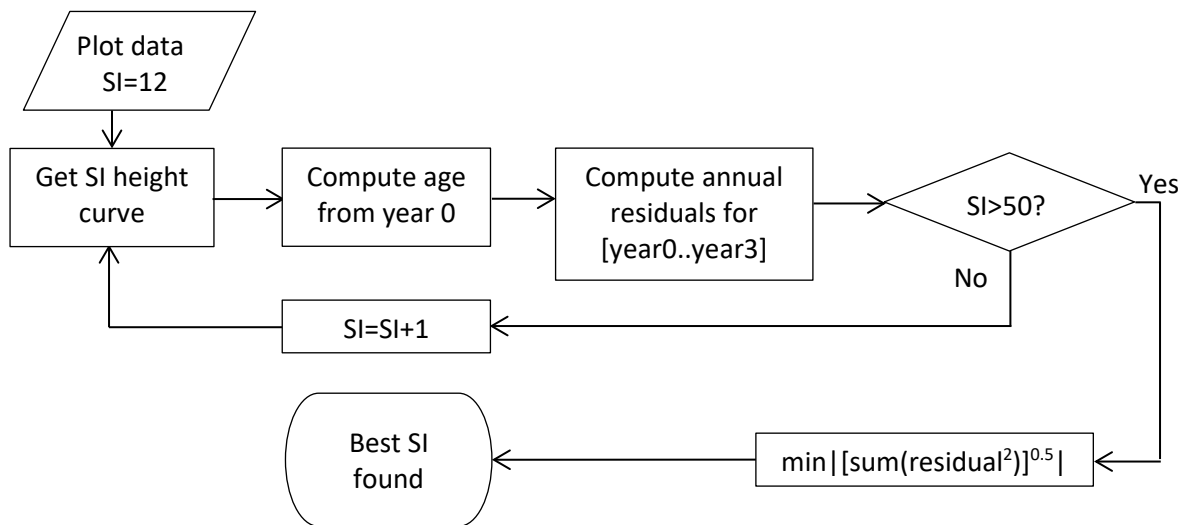


Figure 5. Flow chart of the plot-wise determination of site index from the series of remote sensing based heights (TanDEM-X or ALS data).

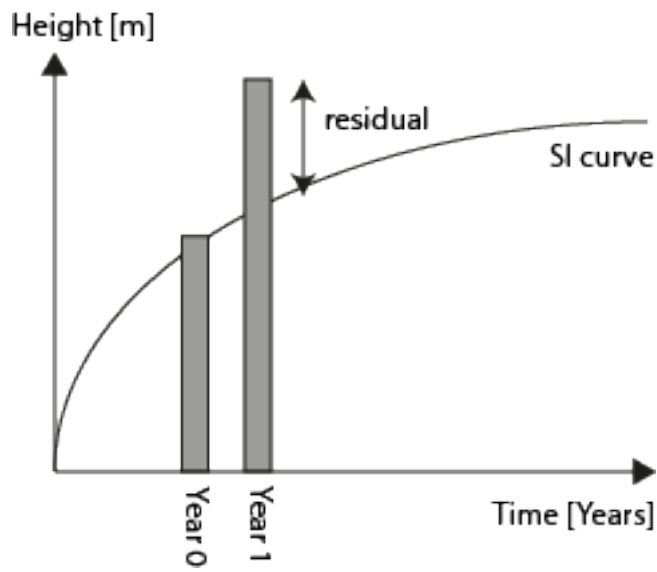


Figure 6. Illustration of how the height measures are tested against the height development of different site index curves and then the min of squared residuals is found.

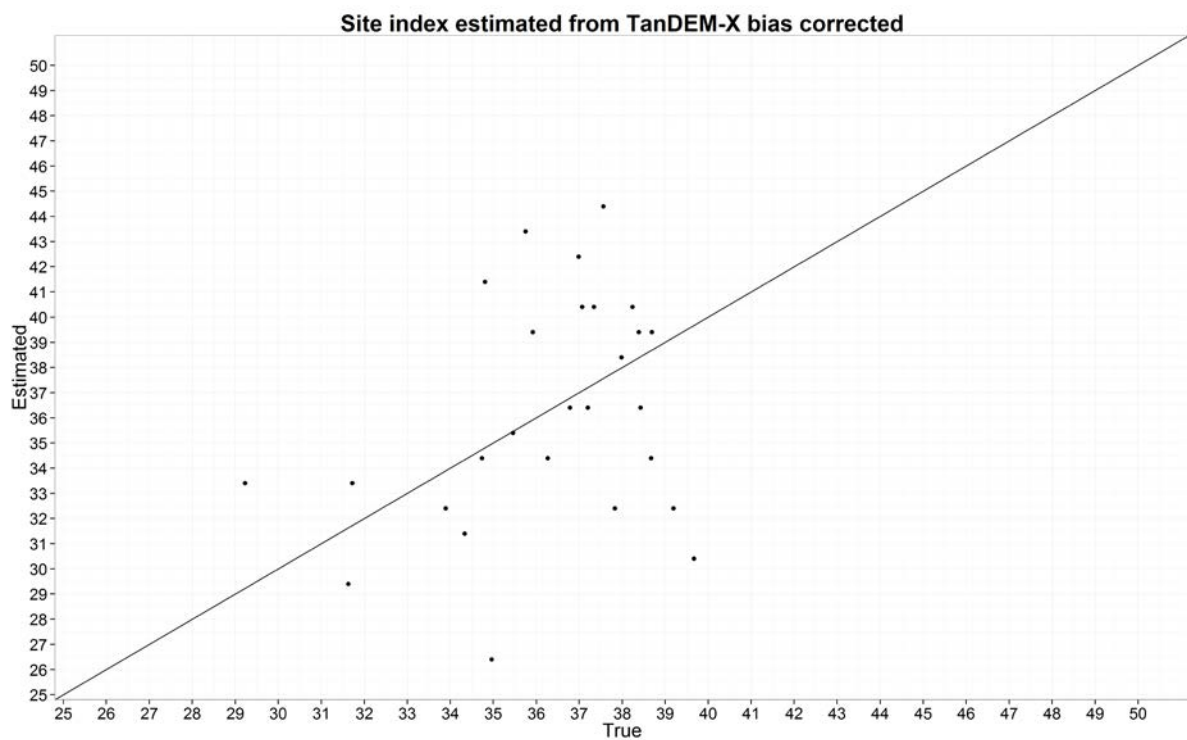


Figure 7 a). Scatter plot of the site index estimation in coniferous forest based on bias corrected TanDEM-X data calibrated against Lorey's mean height. RMSE=4.4 m, 12.1%, $r=0.32$.

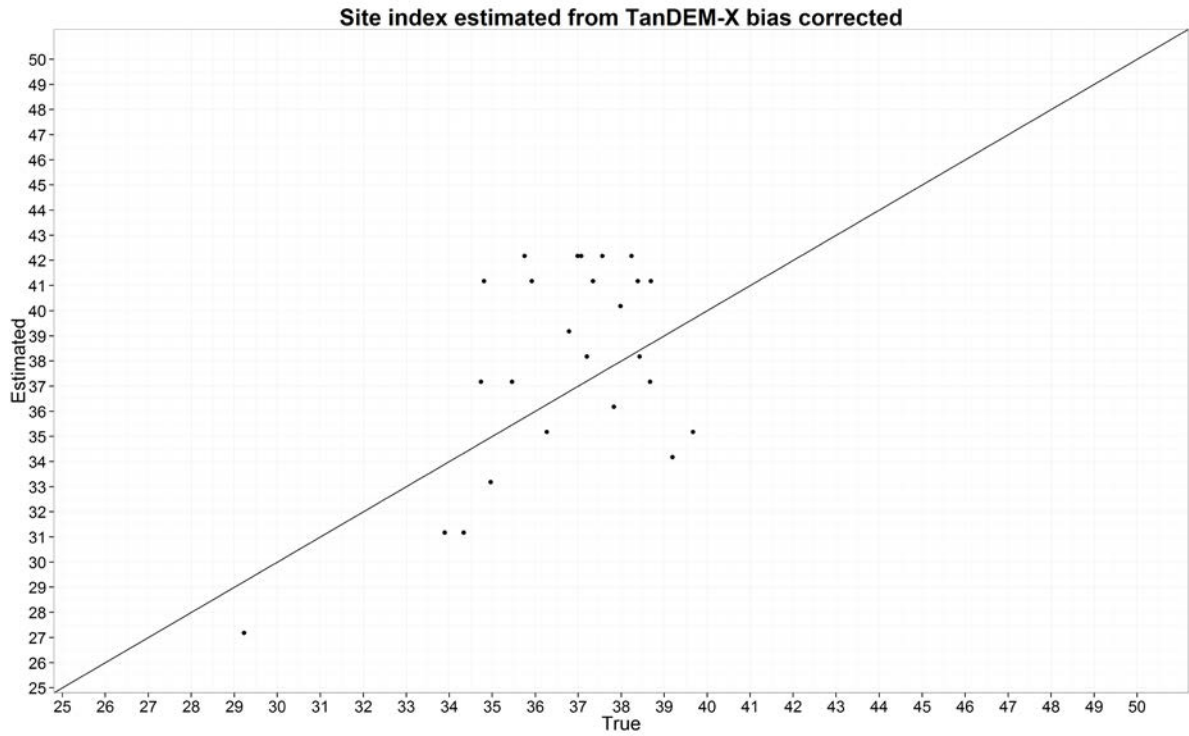


Figure 7 b). Scatter plot of the site index estimation in coniferous forest based on bias corrected TanDEM-X data calibrated against ALS p99. RMSE=5.6 m, 15.5%, $r=0.70$.

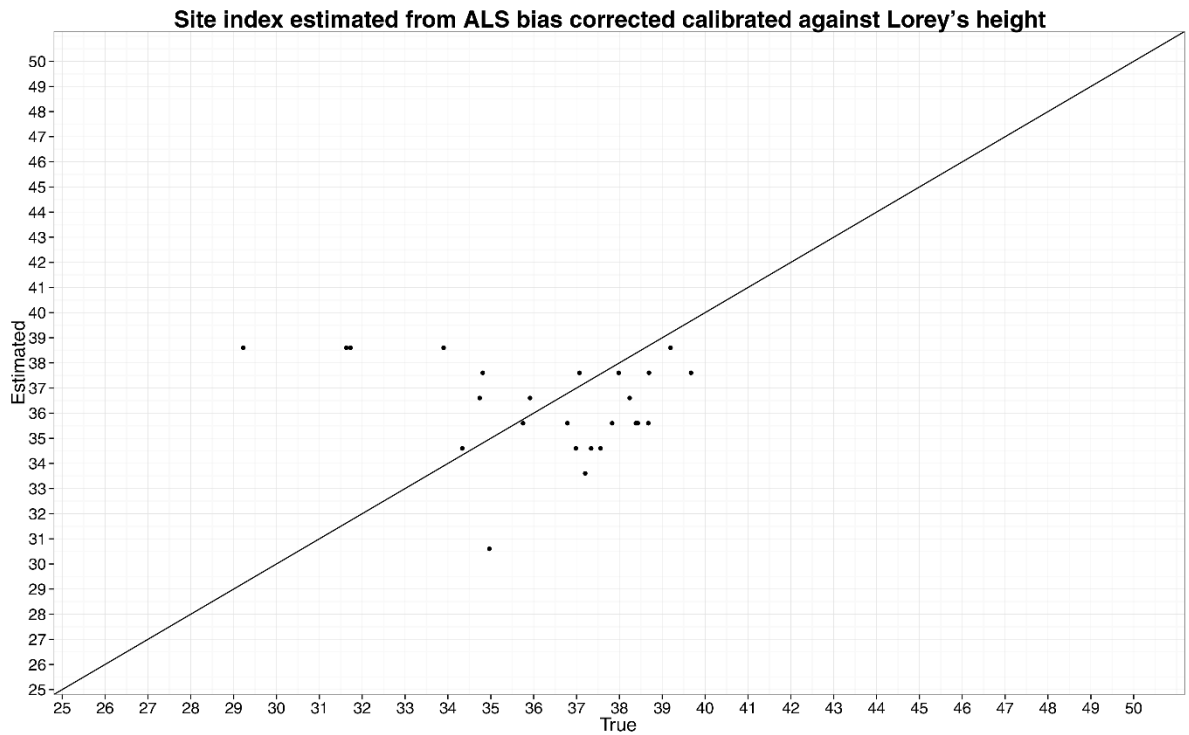


Figure 7 c). Scatter plot of the site index estimation in coniferous forest based on bias corrected ALS data calibrated against Lorey's height. RMSE=10.4 m, 28.7%, $r=-0.25$.

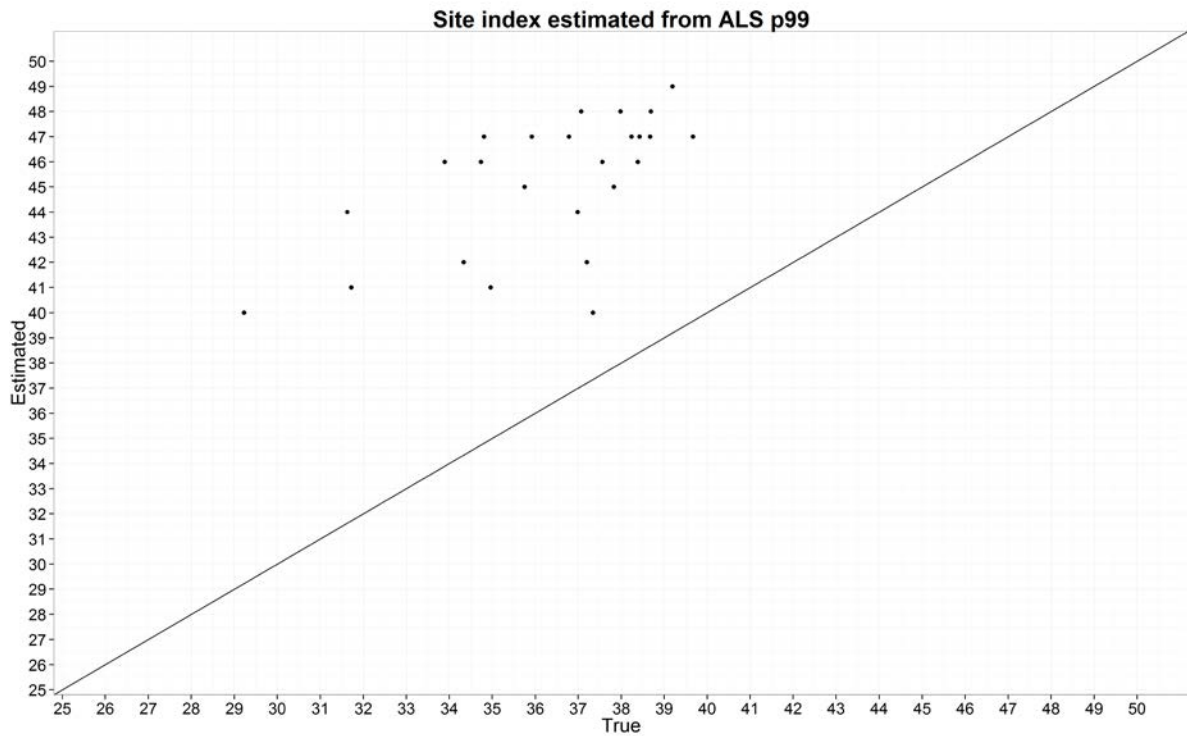


Figure 7 d). Scatter plot of the site index estimation in coniferous forest based on ALS p99 data with no calibration and no bias correction. RMSE=9.2 m, 25.4%.

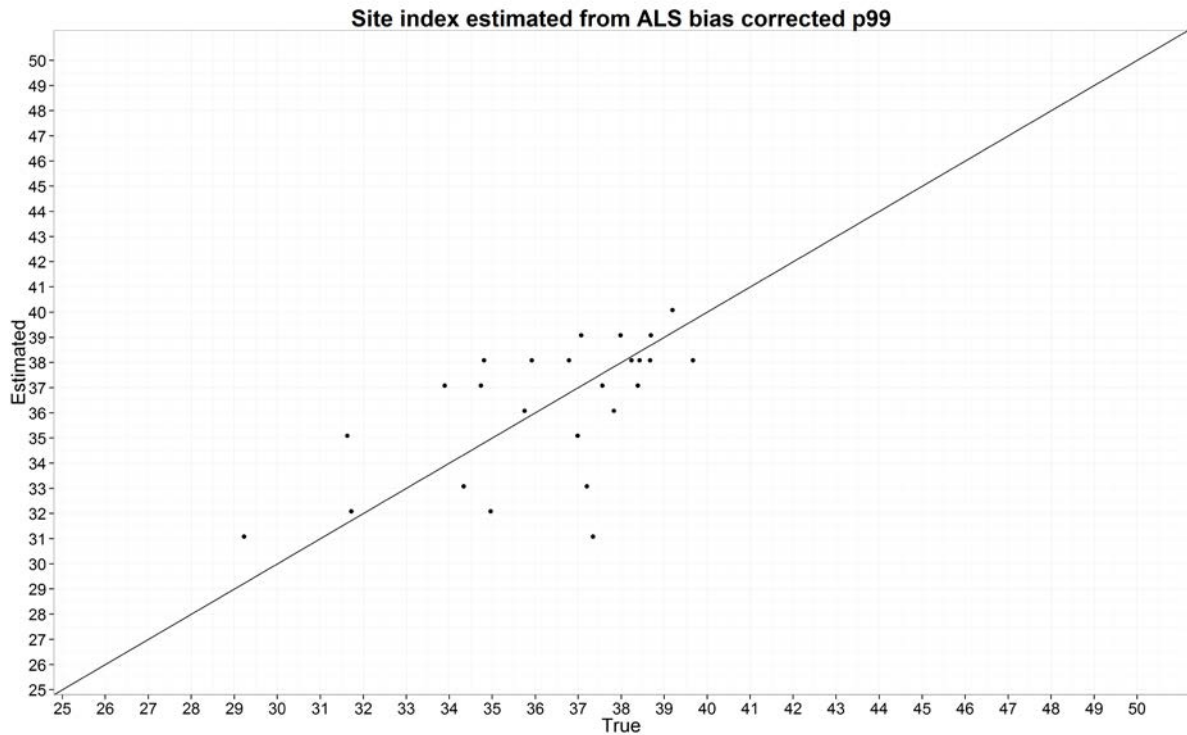


Figure 7 e). Scatter plot of the site index estimation in coniferous forest based on bias corrected ALS p99 data with no calibration. RMSE=2.3 m, 6.3%, $r=0.61$.

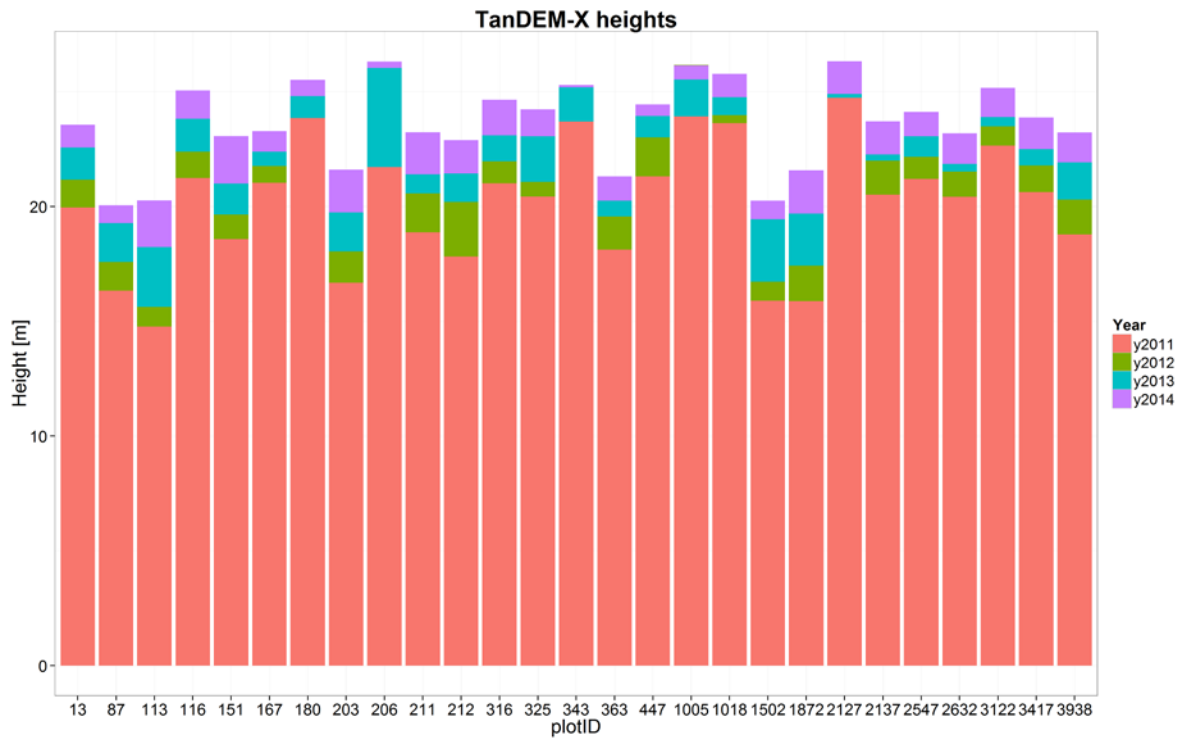


Figure 8. Bar plots of detected height change from TanDEM-X data throughout the years. 2012-2014 show only the height growth compared to 2011.