YRKESHÖGSKOLAN NOVIA

Preharvest efficiency of Trestima, airborne laser scanning and forest management plan data validated by actual harvesting results and forest engineer preharvest estimations

Tatiana Dunaeva

Thesis for Bachelor of Natural Resources

Degree Programme in Sustainable Coastal Management

Raseborg 2017

BACHELOR'S THESIS

Author: Tatiana Dunaeva

Degree Programme: Sustainable Coastal Management

Specialization: Forestry, Economy

Supervisors: Anna Granberg (YH Novia), Johnny Sved (YH Novia), Kaj Hällfors (YH Novia)

Title: Preharvest efficiency of Trestima, airborne laser scanning and forest management plan data validated by actual harvesting results and forest engineer preharvest estimations

---

Date: 17 March 2017 Number of pages: 98 Appendices: 3

Abstract

The present study compares the accuracy of forest attribute estimates, delivered by airborne laser scanning data, conventional stand-wise forest inventory in the form of Forest Management Plan and Trestima forest inventory app, in the context of real preharvesting situation in 2016, with the forest stock sold on stump. The measurements are validated by actual results of commercial harvesting, measured and registered by a harvester's measurement system during logging. There were also available preharvesting estimations carried out by a forest engineer acting on behalf of the forest owner, who arranged the timber sale, which as well became a part of the study as an additional subjective element for comparison.

The aim of this study was to compare the accuracy of the three inventory methods and to find the most accurate and informative method of measurement in the preharvesting conditions from a forest owner's point of view. The compared parameters were set according to the harvesting report, i.e. timber total volume, volumes per tree species, number of stems as well as timber assortment volumes. Trestima turned out to be the most accurate and effective in predicting preharvest stand characteristics, stand-level-wise.

Language: English Key words: airborne laser scanning, commercial harvesting, forest engineer, forest management plan, forest owner, harvesting report, preharvest inventory, retention trees, saw log, stand-wise forest inventory, timber assortment, timber sale, total standing volume, Trestima.

Table of Contents

Abbreviations

ABA – area-based approach;

ALS – airborne laser scanning;

BA – basal area (also could be referred to as G);

Birch – European white birch (*Betula pendula*);

D – diameter;

DBH – diameter breast height;

FE – forest engineer;

FMP – forest management plan;

H – tree height;

LiDAR – Light Detection and Ranging;

N – number of tree stems;

NOVIA – NOVIA University of Applied Sciences;

Pine - Scots pine (*Pinus sylvestris L.*);

PMP - Pystymittaus ja Palkanlaskenta - Measurement of standing trees and Calculation of salaries;

Quality requirements - "Suomen Metsäkeskuksen metsävaratiedon laatuseloste" (the Finnish Forestry Centre requirements to the quality of the forestry data);

RS – remote sensing;

RMSE – root mean square error;

Spruce - Norway spruce (*Picea abies (L.) Karst.*);

STM data – stem data;

SWFI – Stand-wise Forest Inventory;

V – volume.

1 Introduction

Forest inventory is a typical operation in forest management, which is performed in order to give a qualitative and quantitative estimation of a growing stock to further plan future forest management activities, yield and sales.

Forest mensuration can be performed in several ways including, when it comes to large stands, remote sensing techniques of different kind, such as satellite imagery interpretation or an airborne laser scanning or, at small stands, harvesting sites or individual forest compartments, a conventional terrestrial stand-wise forest inventory using relascope or fixed radius sampling. Currently there are also fast smart mensuration techniques on the market, which are constantly developing their accuracy.

When considering an individual site level for the purpose of harvesting plans, the practical designation of the forest inventory is to give more precise preharvesting data in order to determine the timber quantity and quality, as well as notion of incomes. Imperfect information on stand properties and possible value recoveries can lead to a decrease in net income.

Currently in Finland 80% of timber bought from the private owners is sold on the stump (Mäki-Hakola & Rintala, 2015, 195). Trees are harvested in this case for the most part using cut-to-length system, bucked and measured by a logging machine harvester under the operator's management and control in the situation, when the rights to the standing forest already belong to the timber buyer.

In order to estimate the economic value of the timber, the owner needs to estimate the total volume, tree species and assortment volumes. According to the statistics by the Natural Resources Institute Finland LUKE, the real stumpage price per m^3 saw log has been roughly three times as high as per m^3 pulpwood of the same tree species (LUKE, 2016). In order to achieve the highest income, the owner should be able to find the buyer ready to pay the highest price for the timber, taking into account its most valuable parts. Without assortments predictions it is difficult to compare bids.

It is however obvious, that it is of mutual interest to all parties involved to operate as accurate, objective and quickly obtained forest data as possible. The forest industry in Finland has been for a long time interested in developing preharvesting inventory techniques giving more accurate information for the purpose of forest management and production planning (Uusitalo, 1997). Overestimated timber volumes may lead to both higher capital and operational expenditures as well as underestimations may cause interruptions both in harvesting operations and in the long run poor time scheduling at the production sites. However, the lack of objectiveness also directly influences interpersonal relations, trust between the involved parties and goodwill of the forest owner/engineer.

In principle, prior information needed for the estimation of timber volumes and assortment per tree species recoveries can be provided with the use of existing inventory data or by a new ground sampling done by different means.

The traditional sampling, which has been used for many years as the tool for forest inventories possesses such major issues, as quite low accuracy of measurements and lack of objectiveness (Haara & Korhonen, 2004), as well as it may be labour-intensive, as in case of PMP field measurements system, which was based on measuring the DBH of every tree (Pystymittaus ja Palkanlaskenta - Measurement of standing trees and Calculation of salaries, PMP-ohje, 1982). The costs and time efforts affects expenditures of a forest owner and/or a forest engineer for the site preparation activities, i.e., finally affects self-cost of the timber as well as efficiency of, e.g., the forest engineer's work. The PMP system was abandoned by 1990, exactly due to the fact that it was too laborious and expensive (Peuhkurinen et al., 2007).

Equally, methods based on the use of existing information, e.g., forest planning data, may produce certain unreliability, as the data may be out-dated or lack the full areal coverage.

The situation with forest stand characteristics prediction has been improving during the past two decades, when the three-dimensional air-borne laser scanning (ALS) methodology appeared. In Finland area-based ALS methods have stand-level accuracies for species-specific attributes similar to traditional stand-wise forest inventories (SWFI). The ALS-based total stand estimates are more accurate than SWFI and simultaneously they are more cost-effective (Järnstedt et al. 2012; Holopainen et al. 2010). ALS-based inventory methods are replacing traditional SWFI in the production of stand-level data for operative and management purposes (Peuhkurinen, 2011).

However, there are still shortcomings in ALS measurements. Among them there is complicated data gathering about small-scale objects and young stands (Suomen Metsäkeskus, 2016). Despite the advances in mean stand variables estimations, ALS has not succeeded in providing accurate growing stock descriptions for operative wood procurement planning, e.g., tree quality, tree size distribution and the distribution of the logs in timber assortment classes (Peuhkurinen, 2011). Currently, preharvest information is obtained from ABA, but the data are reinspected by the field measurements with additional inventories if required.

In order to overcome all possible shortcomings, the Finnish Forestry Centre maintains the current forest inventory system based on ALS, aerial images, sample areas measurements, targeted field inventories and information from the forest owners (Suomen Metsäkeskus, 2016). These data are available to the forest owners through membership at the official web-source MinSkog (Skogscentralen, 2017).

From the wood procurement point of view, the information provided by a stand-level forest inventory alone is not sufficient. Timber buyers and wood procurement managers search for solutions to get more information for wood procurement planning without laborious field measurements. However, even better computational methods require stand-level forest inventory information, and the key success point here is that these data are up-to-date and reflect the operative stand delineation (Peuhkurinen, 2011).

In such circumstances, any other solution, that may provide independent and objective data, could do more benefit to both the forest owner and the timber buyer. Some examples of such approach have been shown recently on the market among big companies in Finland (Metsä, 2016). The smart forest inventory tool Trestima appeared only in 2012, and already in 2016 it became officially recognized by such a prominent forest market player as Metsä Group as means for forest information update for its Group members.

The solution developer Trestima Oy announces good enough accuracy of the tool – "less than 5% error for total basal area can be achieved" (Trestima, 2016). From the technical side it was described by Rouvinen (2014a and 2014b). The Trestima app for SWFI is based on image analyses of photos taken with a smartphone and transferred to the Trestima cloud service. The application works both online and offline. The operator can follow the results and standard error in real time.

Thus, Trestima may be considered as an accessible solution that can assist in reinspecting the stand and collecting the actual forestry information in preharvesting situation.

The present thesis considers the real case of two forest compartments in Southern Finland, for which there were available forest management plan (FMP) and raw ALS data. The forest stock was sold standing and the harvesting was to fall on spring-summer period of 2016. The situation favoured the use of Trestima and further comparison of all the three forest inventory techniques (Trestima, FMP and ALS) with each other and to the harvesting results. There were also available preharvesting estimations carried out by a forest engineer acting on behalf of the forest owner, who arranged the timber sale, which as well became a part of the study as an additional subjective element for comparison.

The due logging was planned to become means of accuracy verification in terms of total volumes and volumes per tree species. The actual saw log share was also to be compared, as the saw log in this case was the most valuable part of the stock, and thus this comparison was able to bring out the most accurate measurement method in terms of income prediction.

This study considers in principle the comparison of different inventory techniques, such as manual measurements using relascope and ocular estimations, ALS method, official forest management document FMP and Trestima in the operational environment. Under the forest inventory of this specific problem is meant forest attributes acquisition on a harvesting site, such as tree species, tree heights, tree diameter at breast height, timber volume, basal area, number of stems as well as percentage of logs.

2 Research background and theoretical framework

The research background in the case of the study concerns two areas. The first is the investigations of accuracy and errors of conventional SWFI, ALS and Trestima in different conditions and the previous attempts to compare accuracy in any combination of the three above-mentioned methods. The second area of theoretical support to this study is the previous use of logging as means of accuracy validation.

2.1 Research on accuracy of conventional SWFI, ALS and Trestima

In Finland the earliest method for preharvest forest inventory was the PMP system, which was based on measuring the diameter at breast height (dbh) of every tree in the stand. Sample trees were measured additionally (diameter at 6 m height, tree height, quality of the tree, etc.) (PMP-ohje, 1982). The method provided accurate estimates at the stand level, but the system was laborious and expensive (Siipilehto et al., 2016).

The accuracy of the traditional stand-wise sampling has been studied by, e.g., Haara and Korhonen (2004), who demonstrated quite large ranges of RMSE at compartment forest inventory of 10.6–33.9% for volumes, 6.6–24.5% for basal area and 10.9–19.2% for basal area-weighted average height. In addition to that, the method is characterized by subjectivity. Delineation of the stands, selection of sample plots and measurement points within the stands are dependent on the people carrying out the inventory. The resulting measurements done by different people often differ from each other (Poso, 1983). This represents an issue of uncertainty in conventional SWFI data accuracy.

In the recent past the possibility of acquiring spatially accurate, 3D remote-sensing information by means of airborne laser scanning (ALS) has become a major opportunity (Holopainen et al. 2014). An ALS forest inventory method is based on application of LiDAR, which performs highly accurate measurements of forest 3D features. At the moment many of the forest inventories in Finland are performed based on ALS as it has been proved to be efficient and cost-effective means of mensuration. LiDAR requires additional optical imagery for species estimation (Järnstedt et al., 2012).

ALS data of low density (~0.5 pulses per m^2) are used to generalize field-measured stand characteristics over a whole inventory area. Compared to SWFI, the ALS-based inventory method (area-based approach ABA) provided a comparable or more accurate estimation of stand characteristics (e.g., stand mean height or mean volume) as well as proved to be more cost-effective (Suvanto et al. 2005; Uuttera et al. 2006; Järnstedt et al. 2012; Holopainen et al. 2010). The high accuracy of height estimation using ALS has been confirmed, e.g., by Tuominen et al. (2014), who reported root mean squared error (RMSE) of 8–9% and by Yu et al. (2015) with respective RMSE 4.61–5.30%. Maltamo et al. (2006) obtained RMSE of ~ 6% for stand-level volume.

However, information about size-distribution, timber assortments and the number of trees has the same reliability as conventional SWFI (Næsset et al. 2004; Holopainen et al. 2010). In general, low prediction accuracy of the species-specific stand characteristics is seen as a weakness of the ABA (White et al. 2013).

Taking into account that the economic value of a forest stand cannot be accurately determined only on the basis of the total stem volume, it means that stem-quality attributes required by the forest industry in practice, such as species-specific timber assortments, cannot be reliably obtained from ALS data (Vastaranta, 2014). Timber assortment recoveries under the cut-to-length method are estimated with the help of different timber assortment recovery models, non-parametric methods based on existing stem databases that includes timber assortment recoveries and bucking simulations for individual stems (Holopainen, 2010).

It is important to note, that the information in remote-sensing (RS) imagery is limited with regard to its capability of predicting the forest characteristics, since not all of them can be distinguished or recognized by airborne sensor. It influences digital and visual image interpretation, regardless of the analysing methods or an interpreter's skills. In addition to that, the accuracy of the ALS data, produced as geo-referenced information in digital map format for all the attributes measured in the field, depends on the correlation between the auxiliary and field data used in the process of mathematical modelling (Tuominen, 2007).

Tuominen (2007) showed also, that the estimation accuracy of forest characteristics in most RS-based forest inventories is generally poor at the single sample plot levels, and the RMSE decreases with the increasing size of the inventory unit. Therefore, it is questionable whether the stand-level ALS estimates alone are sufficient and accurate enough to become the basis for the correct silvicultural treatments or cutting decisions. Thus, all stands should be always visited in the field prior to taking any important forest management decisions.

Trestima is a new generation terrestrial forest inventory tool, which is based on application of a mobile gadget app. Trestima automatically detects species and calculates forest basal area (using a relascope principle with a dynamic factor), number of stems, diameter distribution as well as in some specific modes of measurements can detect the diameter and height of individual trees from terrestrial imagery captured with the mobile application (Rouvinen, 2014a and Rouvinen, 2014b). Trestima's basal area calculation is fundamentally based on the principles of the Bitterlich (1984) relascope. Trunk widths and heights as well as tree species from each sample are measured and determined in the cloud service.

There are two basic modes of Trestima volume estimation. The first mode employs basal area and measurements of subjectively chosen basal median tree height per tree species. The second one employs diameter distribution of detected trees as well as height estimation based on Finnish forest area specific h(d) functions, where d (diameter) is taken from the diameter distribution by Trestima (Rouvinen, 2014a).

Simultaneously, Trestima gives its own estimation of saw log share based on models of SIMO-calculation system by Simosol Oy. As input data Trestima intakes shapes of the harvesting sites or sample plots, which should be uploaded to both Trestima web-service and mobile app prior to the forest inventory implementation (Trestima, 2016). Reports of species-specific characteristics are calculated from the data extracted from samples and contain all the necessary forest attributes.

There is a number of recent studies concerning the accuracy of Trestima measurements. Vastaranta et al. (2015) evaluated in their study Trestima app for a forest sample plot measurements dominated by Scots pine and Norway spruce in southern Finland. The applied software was TRESTIMA™ Build 132. The estimates from the app were compared to the forest inventory attributes derived from tree-wise measurements using calipers and a Vertex height measurement device.

They concluded that the biases in BA measurements varied from 11.4% to 18.4% depending on the number of images per sample plot and image shooting locations. The RMSEs in BA varied from 19.7% to 29.3%, respectively. Trestima obtained reasonable accuracies for mean average height, where RMSE varied from 10.0% to 13.6% and bias - from 5.0% to 8.3%, with tree heights underestimated for all the tree species (-1.0 – 1.8 m). Diameter measurement bias varied from (−)1.4% to 3.1% and RMSE from 5.2% to 11.6% depending on the tree species.

In general, four images captured towards the centre of the plot provided more accurate results than four images captured away from the plot centre. Increasing the number of captured images per plot to the analyses yielded only marginal improvement to the results.

Since Trestima is based on automatic image interpretation, the authors supposed that the quality of the images, sharpness and light as well as visibility were very important to the results quality, especially when heights were measured.

Here it is important to note that 25 sample plots in this study were of 32 m × 32 m, which is quite a small size in terms of measurement. When the task of measurement is harvesting compartments with varying forms and bigger areas, the results differ. Besides, in this study the researchers used the first mode of Trestima volume estimation, when they subjectively selected median trees and admitted in the study that the errors of selecting median trees were not included, at the same time stating, that "in practice, subjective selection of the median tree will add some amount of error" (Vastaranta et al., 2015).

Kopakka (2015) found that Trestima underestimates individual tree DBH and mean DBH, resulting in underestimation in BA. Vastaranta et al. (2015) instead found slight overestimation (0.8–1.4%) in the DBH of the individual median tree for pine and broadleaves, with 3.1% underestimation for spruce, while tree height and stand basal area were underestimated by Trestima.

The results of Trestima application in boreal forests of Siberia, obtained during some forest inventories by RusFor Consult Oy Ab in 2014–2016, show that on the area of 2.6 x 10^6 ha (with 599 sample plots of size 1–2 ha each) RMSE achieved 18–23% in volume estimations, 17–20% - in BA estimations (RusFor Consult Oy Ab, 2016).

It should be also taken into account that Trestima is under continuous development work; hence, it is important to note which version of the processing software was applied in these studies and practices.

2.2 Research on comparing the methods' accuracy

Unfortunately there are only few available recent studies on the subject of comparing the accuracy of simultaneous Trestima, ALS and SWFI measurements. The studies might also have various other aims of research resulting in different set-ups and methods.

For instance, in 2010 Holopainen et al. compared existing SWFI data with area-based airbone laser scanning (ALS) inventory in the estimation of logging outturn assortment volumes with respect to inventory errors. The results were compared with the reference series measured by the logging machines. The most significant source of error in the prediction of clear-cutting assortment outturns was the inventory error (as compared to the errors related to stem form predictions, stem distributions and simulated bucking).

The RMSE statistics on estimation of the clear-cutting compartment value were 25.8% for the ALS inventory and 29.1% for SWFI. The ALS data resulted in slightly more accurate estimates, however the results were biased. The authors make a conclusion, that "operative preharvest measurement would require more accurate input data than current SWFI and ALS inventories", and both "methods should be developed further" (Holopainen et al., 2010).

However, the closest and the most recent research in regard to the present study was carried out by Siipilehto et al. (2016). The authors compared the results of the predicted stand structure for Scots pine-dominated clear-cut stands delivered by ALS methods, Trestima and preharvest measurement tool EMO (Uusitalo and Kivinen, 2000). EMO as well as Trestima requires stand-specific field measurements for prediction as opposed to ALS methods.

There were seven stands chosen for the purpose of the study with areas ranging from 0.7 to 2.0 ha. The estimates of diameter-height distributions based on each method were compared to accurate tree taper data of logs bucked, measured and registered by the harvester.

According to the results, grid-level ABA and Trestima 10 (ten shots per stand against the other variant Trestima 5) proved to be generally the most accurate methods for predicting diameter-height distribution. Goodness of the distribution fit test also resulted in good performance in standard stand and assortment characteristics. Both methods had their strengths and weaknesses. ABA-grid and Trestima gave the following accuracy (RMSE, %) at predicting forest variables respectively: 35.4 and 34.2 for number of stems (N), 26.0 and 31.1 for basal area (BA), 10.6 and 8.2 for BA-weighted DBH 9.3 and 14.6 for BA-weighted height, 32.7 and 38.0 for total volume (V).

Siipilehto et al. (2016) in this study note, that ABA results were generally in line or slightly worse than in other ABA studies carried out in the same study area (Holopainen et al. 2010; Yu et al. 2010; Vastaranta et al. 2013). Trestima turned to be quite sensitive to the number of photos in the analysis. A sample of 5 images was sufficient to reach 10% standard error in BA in only two stands. However, in reality Trestima users can follow the results and standard error in BA in real time to reach the target accuracy.

The study concluded that Trestima did provide the most accurate stand characteristics at their research obtaining 23 score points against 20 points by ABA-grid in the final methods ranking which was based on number of the best and worst cases among the analyzed criteria. Nevertheless, it is important to mention that it is the only study at the moment where Trestima has been scrutinized at such a deep level as well as it is equally important to mention, that Trestima at that study was used in a different way than when it is applied operationally.

An additional merit of the study was the comparison of expenses needed for the implementation of the best methods. From the compared methods ABA was the least expensive, the Trestima method became the second least expensive and the EMO method was the most expensive. Since ABA seemed rather trustworthy in predicting stand characteristics prior to harvesting, if up-to-date ABA information is available, it was concluded that it is more cost-effective to use ALS data in stand-specific inventory than Trestima.

Taking into account that the ALS method itself has not succeeded in providing accurate information on distribution of the logs in timber assortment classes, additional models are used to derive saw log and pulpwood (e.g., Peuhkurinen, 2011). The current thesis does not aim at studying the effectiveness of these applied methods and therefore this issue is not considered within theoretical background research.

2.3 Harvester as means of accuracy validation

The logging machine is often used in the studies, where researchers want to check the accuracy of the measurement methods (Leitner, 2014). Data obtained by the logging machines are used in most cases as the reference data both for clear-cutting and thinning cases when validating ALS data (e.g., Korhonen et al., 2008; Bollandsås et al. 2010; Holopainen et al., 2010; Maltamo et al. 2010; Peuhkorinen, 2011; Vastaranta et al., 2014).

A harvester gathers STM (stem) data according to the Standard for Forest Data and communication, where according to the purpose of the studies there might be included information for each felled tree regarding the logging machine's position at the time of felling, stem diameters at 10-cm intervals from the stump height to the final bucking height, tree species, bucking parameters and bucked assortment volumes (Holopainen, 2010). Stem distribution series, assortment outturn volumes and mean stock characteristics (BA, D, H and V) for each clear-cutting compartment can be derived, using stem diameter and length information from the STM files.

There are no common standards on harvester head measurement accuracy (Strandgard and Walsh, 2012, 8). However, in terms of operational applications such data are the only reliable source of information, which can be considered accurate enough. A harvesting machine head is a complex mechanism, which measures both diameter and length of the tree trunk, being the components for volume calculation. Provided that a harvester's head is calibrated and maintained according to the machinery specifications, the error tends to be at its minimal values.

According to the Ministry of Agriculture and Forestry Regulation Nr 12/13 dated June 17, 2013 (Dnr 1323/13/2013) no systematic errors can be accepted in any official wood measurement method. The required accuracy for lots exceeding 10 m^3 measured by a logging machine is ± 4% for each timber lot of the true volume.

Leitner et al. (2014) in their study on harvester and processor length measurement errors investigated on determining factors affecting these errors and evaluating the economic effect of over-length logs. With the specification minimum log length of 406 cm, the analyses of the sawmill data showed that 73.7% of the logs were longer than 412 cm. Logs were on average 1.8 cm longer in winter. There was no difference between head type. Professional calibration of the heads resulted in an improvement in precision and accuracy of the measurements. For the two harvester heads it was possible to achieve a log length measurement precision, where 58% or more were within 0.5 cm, and 96% were within 2.5 cm. However, the differences in volumes caused by discrepancies in minimum and actual log length were within the limits for accuracy of a harvester wood measurement method in Finland which accepts ± 4%, as mentioned above.

It is crucial to mention that logging in all these studies are done for non-commercial purposes. Though, there is some research aiming at fitting the ALS methodology into wood procurement process (e.g., Peuhkurinen, 2011), with saw log recovery models including reductions due to bucking constraints (allowable length and diameter combinations, and external technical defects), which still need improvement.

The principal difference between the theoretical recovery and commercial harvesting results is that in case of commercial harvesting we get only the volumes the buyer decided to pay for. Discrepancies can arise out of a buyer's preferences in bucking diameters and lengths (tree tops and waste wood volumes might rise). Peuhkurinen et al. (2008) and Piira et al. (2007) showed separately in their studies, that the saw log recovery is dependent on the bucking parameters used. E.g., in Piira et al. studies (2007) the saw log recovery declined by 2.5% in pine stands and by 2% in spruce stands, after the minimum length had been increased by 9 dm (from 31 to 40 dm).

Furthermore, besides the bucking preferences there is also to some extent unpredictable variable of trees defects: root rot, insects, knots, illnesses, stem form deformations may unpredictably reduce commercial timber. These parameters influence the total volumes of harvested wood, volumes per tree species and log/pulp breakdown, timber value and finally income.

There are developed models for the prediction of theoretical and factual saw log volume which take into account the reduction due to defects (as, e.g., by Korhonen et al., 2008, and the model of Mehtätalo, 2002). At that, even the effective models may overestimate factual saw log volume, especially in case of unpredictable defects.

However, the goal of this study was not to verify the correctness of the models, yet it was to consider quality and reliability of the raw data available to a forest engineer in a real preharvesting situation and their applicability. Besides, for a Trestima user and those who receive income from timber sales it is always interesting and useful to know, what the real accuracy of the measurement system is as compared to the actual volume of growing stock.

That is why for practical purposes clear-cut commercial harvesting might be relevant to use, especially in the preharvesting situation. The method clearly has its limitations. It does not show precise DBH, BA, total heights. However, it shows the minimal usable volume, species-specific volumes and actual share of saw log, i.e. the basis for the real income. Number of stems, shown in some harvesting reports in a way that can be compared with the corresponding preharvesting measurement, is of a special advantage, especially in case with Trestima, where this value is used for further system calculations, or in case, when the pricing can be done per stem.

According to the data provided by RusFor Consult Oy Ab (2017), the head official representative of Trestima in Russia for 2014-2016, the results of some Trestima applications in Leningrad, Komi and Arkhangelsk regions during that period show the following difference between the preharvest measurement and final felling results: ± 2–5% for 4 thousand m^3, ± 1% for 38 thousand m^3, ± 5% for 41 thousand m^3 and + 11% for 23 thousand m^3. The mean overall results are more accurate, however per each harvesting site the differences might reach higher values.

These statistics should help to develop measurement systems techniques, as well as models for the prediction of theoretical and factual recoveries, including saw log share.

3 Purpose and Research Question

3.1 The distinctive features of the current study

The key difference of the current study compared to earlier studies is that there were no special ALS and conventional SWFI measurements of the harvesting areas done by the author for the purpose of the study. Only Trestima was applied specially for this research, whereas ALS and FMP data were available at that time for larger-scale areas with the given quality, in the state “as is”. In this sense, this may be regarded as a unique composition of input parameters, as no control of the quality of these prior measurements had been done to the moment. If there were errors, it was impossible to define their source and subjectivity. Moreover, the used data were interpreted and transformed from bigger areas to stand-level.

However, the actual preharvesting situation, when the forest owner needs to take preharvesting decisions on the basis of the given data that can't be regarded as tailored and fully reliable, and, moreover, it is the buyer, who is responsible for cutting and measuring timber, was a clear benefit to this study. Its results may show the difference not only between the accuracy levels of measurement techniques, but also between their theoretical and actual accuracy levels, as well as between large-scaled data and extracted stand-level data.

Commercial harvesting with all its shortcomings for the research purposes nevertheless shows the minimum level of logging, since factual recovery is below theoretical. Simultaneously actual logging results can be obvious, i.e. the real income and the difference in the forest owner's expectations and reality. If a method shows volumes less than actually might be commercially harvested, it gives lower expectation to the forest owner and possibly more space for commercial manoeuvre to the buyer. The latter might be an issue for further investigations, since it is a behavioural matter of a seller's confidence and a buyer's reaction.

Imperfect information on stand properties and possible value recoveries can lead to a decrease in net income. Korhonen et al. (2008) refers to Hubbard and Abt (1989), who noted that support provided for forest owners during timber sales, including technical on-site and market assistance, increased their returns, especially in the case of highly valued stands. In the current study this fact is also related to the actual preharvesting situation and amount of information, contained by the methods under consideration.

3.2 The objective and goals of the study

The aim of this study was to assess and compare the accuracy of the three inventory methods in predicting timber volumes in boreal forest sold standing stands in actual preharvesting conditions. The investigated methods were Trestima, Airborne laser scanning (ALS) and conventional Stand-wise forest inventory (SWFI) in the form of existing Forest Management Plan actual for that harvesting area. All the three methods are available to a forest owner as a basis for the commercial decisions in preharvesting situations.

The predicted volumes based on these methods were compared to commercial harvesting data measured and registered by a harvester's measurement system during logging. The harvesting data were also compared to preharvest estimations of a forest engineer responsible for arranging the timber sale, presented as a subjective expert judgement and reference.

The specific tasks of the thesis were:

- to investigate the efficiency of the three methods to estimate timber volumes of the forest stands sold on stump;
- to compare the basic forest attributes generated by these three methods of forest inventory in order to see the possible sources of errors;
- to examine the proximity of the saw log shares estimated by the methods to the actually harvested saw log share and volumes in order to see the difference between theoretical and factual saw log recoveries;
- to compare an expert's preharvest estimation with the other methods and harvesting results; and
- to find the most accurate and informative method of measurement in the preharvesting case.

The goal is to consider final discrepancies in preharvest stand characteristics (stem number, total volume, tree-species volume and log percentage) and reveal the most informative method of forest inventory giving the nearest estimations to the harvesting results, stand-level-wise.

4 Methods and materials

4.1 Study area

The forest stand of interest is located at the place of Falkgölen (approx. 60°0'50.78"N, 23°24'35.29"E) (see Fig. 1) in the municipality of Raseborg in South-Western Finland. It is a typical Southern Finnish managed boreal forest area and has been managed by Novia University of Applied Sciences (hereinafter also referred to as NOVIA). The total area of the estate constitutes approximately 220 hectares.

The study considers two forest compartments with ordinal numbers 466 and 482 located within the boarder of the forest estate, where a forest engineer of NOVIA had assigned a final felling.

Fig. 1. Study area Falkgölen

The actual harvesting sites were allocated and marked inside the forest compartments (see Fig. 2). Each harvesting site had biotopes. The areas of the harvesting sites account for 1.9 and 4.4 hectares, respectively. The site fertility classes (Cajander, 1949) in the study area are as follows: dominating *Calluna* type (CT) at the upper compartment 466 and dominating *Vaccinium* type (*VT*) at the lower compartment 482.

The area was dominated by coniferous tree species. According to the Forest Management Plan dated 2014, the upper harvesting site (466) was covered mainly by Scots pine (*Pinus sylvestris* L.) forest of approx. 110 and 210 years old, and the lower harvesting site (482) was almost equally represented by Scots pine and Norway spruce (*Picea abies* (L.) Karst.) forest of approx. 180 and 60-180 years old, respectively. Deciduous trees, mainly birch species (*Betula pubescens* Ehrh. and *Betula pendula* Roth), were minor components of the stand.

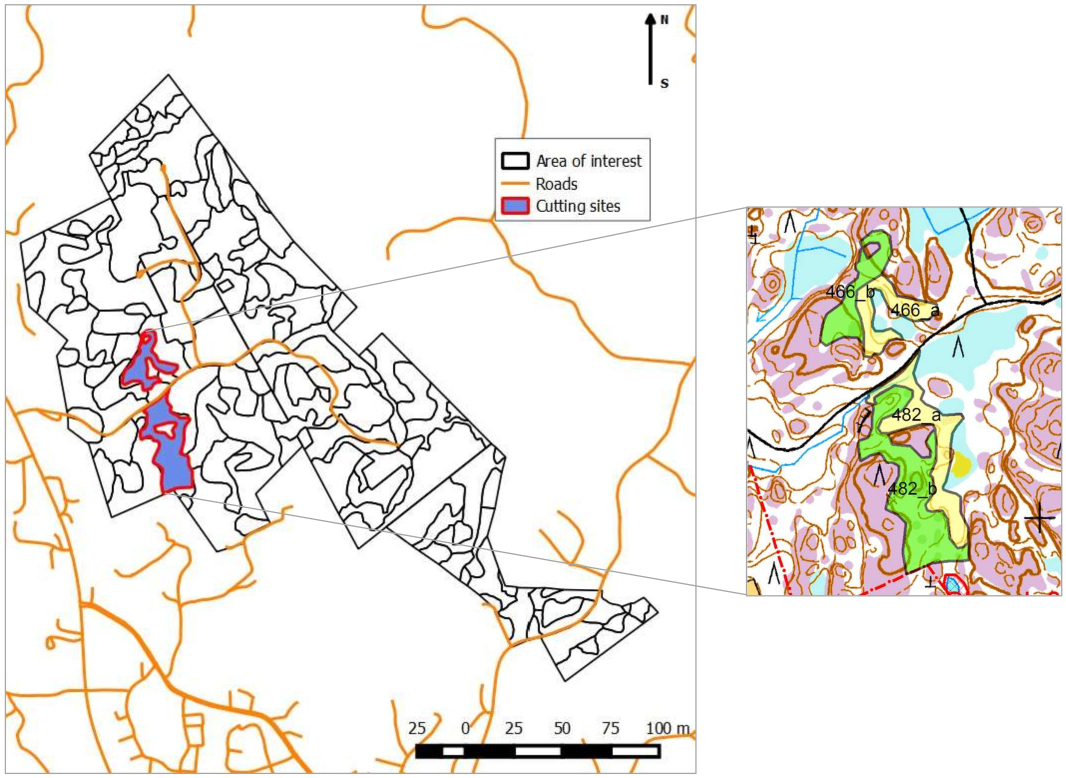


Fig. 2. Harvesting sites (upper compartment 466 and lower compartment 482)

Novia sold the standing timber on these sites to a company, which proceeded with harvesting in May 2016. Thus the logging in the study area was carried out in the form of commercial harvesting. The harvesting method applied was clear-cutting with retention trees to be left in accordance with the current Finnish PEFC-certification requirements and best logging practices. The measurement method was cut-to-length, with harvested volumes registered on the spot by the logging machine.

4.2 Data and materials

For the purpose of the study the following materials and methods were used (a general list):

- cartographic and GIS materials for Falkgölen area;
- Forest Management Plan (FMP) by the Finnish Forestry Centre, updated in 2014;
- airborne laser scanning data (ALS) by the Finnish Forestry Centre, dated 2014;
- forest inventory report based on Trestima measurements, prepared in 2016;
- preharvesting forest estimations prepared by NOVIA in January 2016;
- harvesting report, presented by the timber buyer, dated May 31, 2016.

4.2.1 Cartographic and GIS materials and tools

Cartographic and GIS material used at this study consisted of a GIS layer with shapes of the Falkgölen area forest compartments referenced to the projected coordinated system EUREF-TM35FIN (see Fig. 1) and PDF-format maps of the harvesting sites, prepared by NOVIA's forest engineer (see Fig. 2). Later at this study, the PDF-format maps of the harvesting sites were manually georeferenced to the projected coordinate system EUREF-TM35FIN and their shape-layers were created using the free GIS software qgis (version 2.12.0).

4.2.2 Forest Management Plan

One of the very initial materials used in the study, which contains essential forest data, was Forest Management Plan (FMP) issued in 2002 by the Finnish Forestry Centre and updated by NOVIA in 2014 with the help of forest increment models and SWFI.

FMP is a standard document, which is normally used to record data on a forest state, plans for forest development and management activities. FMP is an integral document used by a forest owner and a forest engineer in the course of forest management operations. It includes but is not limited to forest stand maps of different kind, data on cadastral units, on areas, on land use and land cover, diagrams, data on forest development classes and growing stock volumes (also per tree species), historical data on forest damages caused by different natural and/or artificial events, data on valuable habitats, wildlife and biodiversity, data on forest certification schemes, recommended harvesting methods and silvicultural operations, economic indicators such as costs of operations and income estimations, detailed forecast for stands increment and possible volumes to harvest. FMP usually is prepared for a period of 10 years and should be systematically updated throughout its lifecycle (Lehmonen, 2015, 236).

The FMP obtained for the purpose of this study was prepared to its largest part basing on conventional stand-wise forest inventory (SWFI), i.e. visual assessment, ocular estimations, relascope and fixed radius measurement techniques by forest engineers, as well as partly based on remote sensing.

The FMP extract for forest compartment numbers 466 and 482 is presented in the Fig. 3.

RASEBORG / Område 1 / Skogsbruksplan 10 / Post Boställsskosgen Skogsbruksplan är inte utskriftduglig 06.03.2014 Sida 19/90

Figurförteckning

RASEBORG / Område 1 / Skogsbruksplan 10 / Falkgölen / Block 1

Figur	Areal, ha	Ståndort och utvecklingsklass	Beståndsuppgifter: trädslag	ålder, år	volym, m3/figur	volym, m3/ha	timmer, m3/ha	massa, m3/ha	diameter, cm	höjd, m	stamantal, st/ha	gr.yta, m2/ha	tillväxt, m3/ha/år
466	4,9	Karg mo	**Totalt**	**130**	**1096**	**226**	**102**	**122**	**30**	**18**	**490**	**27**	**3,3**
		Stenig medelgrov eller grov momark	Tall	110	706	145	67	77	27	19	310	16	2,3
		Förnyelsemogen skog	Tall	210	259	53	30	23	41	20	50	6	0,5
		Icke utvecklingsdugligt	Gran	70	105	22	2	19	22	13	130	4	0,5
		överårig	Gran	210	26	5	3	3	44	19	10	1	0,1

Avverkningssätt och tilläggsuppgifter	Skyndsamhet	Tillgänglighet	Avverkningsavgång totalt och per trädslag: m3/figur	m3/ha	timmer: tall	timmer: gran	timmer: björk	timmer: annat	massa: tall	massa: gran	massa: björk	massa: annat	Dessutom energivirke, m3	Inkomstkalkyl, €: rotprisintäkter	Inkomstkalkyl, €: ansk.-tillägg
Avverkning i fröträdsställning	2014 - 2018	A	743	153	297	15			319	111				23720	4630

Skogsvårdsarbeten	Skyndsamhet	Tilläggsuppgifter om arbetsslaget	Areal ha	Kostnadskalkyl, €
Mekanisk hyggesrensning	2014 - 2018		4,9	610
Naturlig förnyelse av tall	2014 - 2018		4,9	

Särdrag (hela figuren)

Tjäder, Spelplats

Figur	Areal, ha	Ståndort och utvecklingsklass	Beståndsuppgifter: trädslag	ålder, år	volym, m3/figur	volym, m3/ha	timmer, m3/ha	massa, m3/ha	diameter, cm	höjd, m	stamantal, st/ha	gr.yta, m2/ha	tillväxt, m3/ha/år
482	4,9	Torr mo	**Totalt**	**145**	**1292**	**262**	**126**	**134**	**35**	**23**	**430**	**26**	**3,4**
		Stenig medelgrov eller grov momark	Tall	180	593	120	76	43	39	25	90	11	1,1
		Förnyelsemogen skog	Gran	60	326	66	3	62	21	18	270	8	1,5
		Icke utvecklingsdugligt	Gran	180	339	69	47	21	42	24	60	7	0,9
		överårig	Vårtbjörk	180	33	7	0	6	41	25	10	1	0,2

Fig. 3. FMP extract provided by NOVIA – data for forest compartments 466 and 482

For the purpose of the study the following FMP data were used:

- area of a forest compartment, ha;
- tree species;
- age of the forest, years;
- volumes: total and mean growing stock per tree species, m^3 and m^3/ha;
- mean volume of log per tree species, m^3/ha;
- mean volume of pulpwood per tree species, m^3/ha;
- basal area-weighted mean diameter breast height, cm;
- basal area-weighted mean height, meters;
- number of stems, pcs/ha;
- basal area, m^2/ha; and
- forest increment, m^3/ha/year.

The timber volumes are given over bark. Pulpwood implies also tree tops within its volumes.

4.2.3 Airborne Laser Scanning data

Airborne Laser Scanning (ALS) data were provided by NOVIA. The ALS data originate from the Finnish Forestry Centre and are actual to the year 2014. For the purpose of the study the ALS data were delivered in a shape file (a GIS layer) as a grid of 16x16 meters (see Fig. 4), where each grid cell contained detailed versatile data about the forest state and forest attributes.

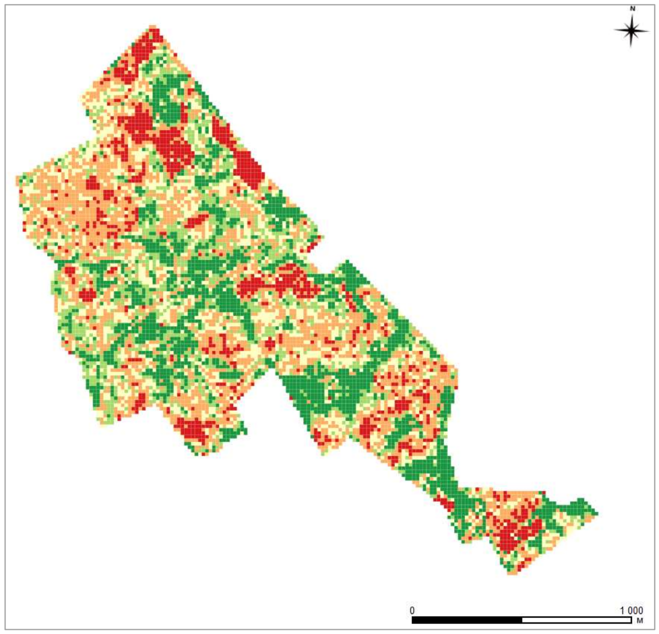


Fig. 4. ALS grid 16x16 for Falkgölen (general view)

The following ALS data were specifically used for the purpose of the study:

- dominant tree species;
- basal area per tree species, m^2/ha
- stem number per tree species, pcs/ha;
- basal area-weighted mean diameter per tree species, cm;
- basal area-weighted mean height per tree species, m;
- mean volume of growing stock per tree species, m^3/ha;
- total basal area, m^2/ha;
- total stem number, pcs/ha;
- total mean diameter, cm; and
- total height, m.

The timber volumes are given over bark. Pulpwood includes tree tops within its volumes. RMSE of the given ALS data could not be obtained.

Unfortunately, the ALS data did not provide in itself the inbuilt share of saw log, and it would be necessary to apply models of theoretical and factual log recovery to get this information. The estimates for the usable trunk part can be produced directly from the trees of the reference plots, or indirectly by using the stem data bank as reference data (Peuhkurinen et al., 2008).

There are several models of estimating log recoveries on the basis of ALS data, which have been tested especially actively the last decade (Peuhkurinen et al., 2008; Peuhkurinen, 2011). The methods produce species-specific saw log recoveries, however, the estimation accuracies should be further improved. As there were no estimates for the usable trunk provided together with the ALS data, it was decided not to undergo the procedure of determining log recoveries on the basis of ALS in the current study, otherwise the errors of the model might influence the accuracy of ALS results compared to the other methods.

4.2.4 Trestima measurements

The mensuration applying Trestima took place in February 2016. In order to perform the forest inventory, shapes of the areas planned for harvesting were uploaded to both Trestima web-service and mobile app as input data.

In the case of the study, according to Trestima's recommendations the following method of measurements was applied. The diameter distribution of detected trees as well as height estimation were obtained by the application based on the Finnish forest area specific h(d) functions, where d (diameter) is taken from the diameter distribution by Trestima. The log share was estimated by Trestima. Measurements of a basal median tree height per tree species were not carried out. The method of Trestima measurements applied in this study is standard, the most simple and can be used in all cases of mensuration. However, the applied approach strived to provide for the unbiased choice of image shooting locations and higher accuracy of the ultimate data.

The fieldwork was performed with the use of Nokia Lumia 925 mobile phone, (Trestima app v3.21 (WP8)) and Sony Xperia Z2 (Trestima app v.1.82 (Android)), the latest app version to the date of imaging. Sampling was made on a systematic basis at preliminary planned sample points without selection of median trees in order to eliminate subjective errors. There were all in all 19 shots on the area 466 and 36 shots on the area 482. The majority of the images was taken towards the centre of the areas. Shapes of the harvesting sites and sample taking locations are shown on Fig. 5.

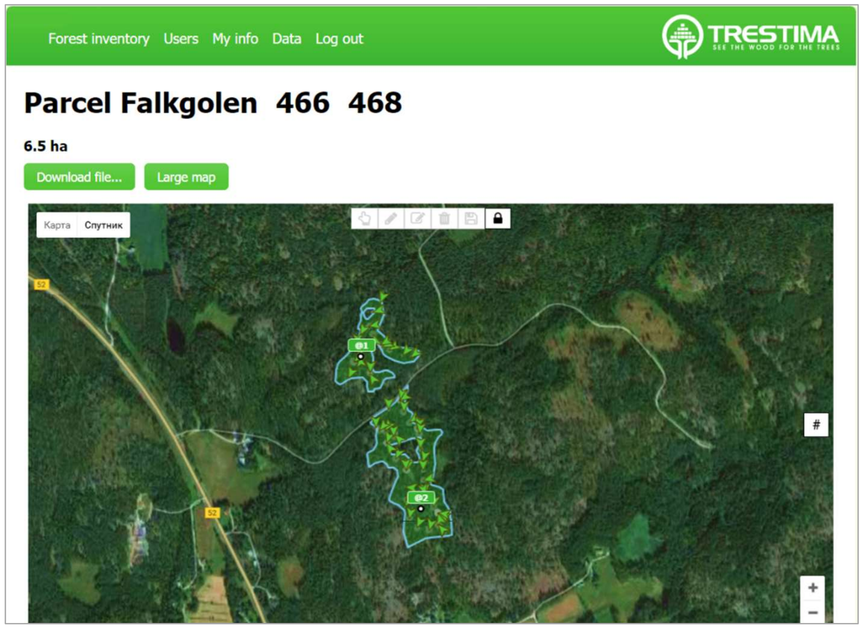


Fig. 5. View of harvesting sites shapes and samples in Trestima web-interface

The number of images, which are referred to and considered as samples in Trestima, was assumed sufficient by the system. As it is illustrated by Fig. 6 and Fig. 7, the achievement of Basal Area (BA) convergence is proved by the straightening BA curves for all tree species on the areas 466 and 482.

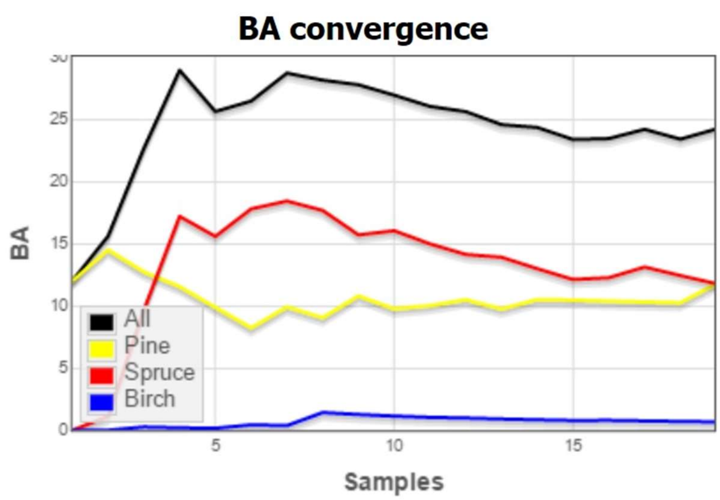


Fig. 6. The Basal Area convergence on the harvesting area 466

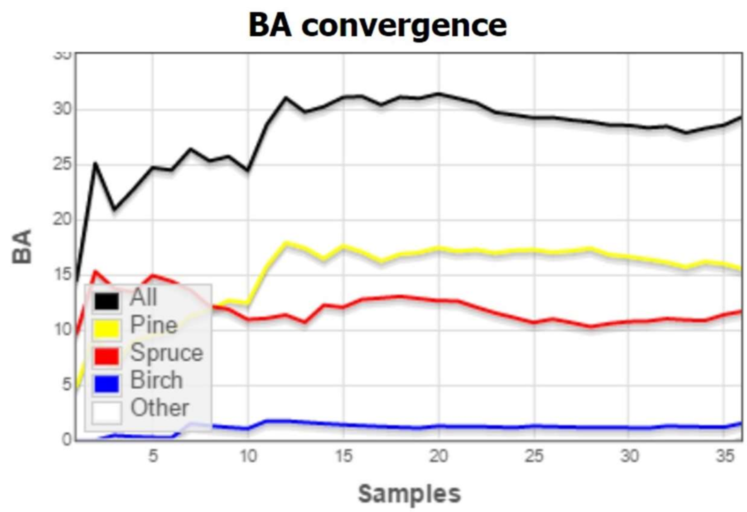


Fig. 7. The Basal Area convergence on the harvesting area 482

The respective reports generated by Trestima are presented in Fig. 8 and Fig. 9. The raw data acquired during the application of Trestima are presented in Annex 2.

Forest inventory report: @1

Measurement performed 01.02.2016
Measured area 2.03 ha
BA sample amount 19 pcs

Specie	BA m^2/ha	Stems pcs/ha	Stems pcs	DBH cm	Height m	Age y	Vol m^3/ha	Vol m^3	Log %
pine	11.7	307	626	22.1	18.2	70	108.1	219.9	47
spruce	11.8	637	1295	15.3	14.1	38	94.0	191.3	36
birch	0.7	35	72	15.6	15.4	38	4.5	9.2	9
Tot.	24.2	979	1992	18.6	16.2	53	206.7	420.4	40

Fig. 8. Trestima report for the harvesting area 466

Forest inventory report: @2

Measurement performed 01.02.2016
Measured area 4.45 ha
BA sample amount 36 pcs

Specie	BA m^2/ha	Stems pcs/ha	Stems pcs	DBH cm	Height m	Age y	Vol m^3/ha	Vol m^3	Log %
pine	15.5	278	1240	26.7	20.9	91	156.3	696.0	59
spruce	11.7	536	2388	16.7	15.1	41	97.5	434.2	38
birch	1.6	52	230	19.6	18.1	50	11.6	51.7	24
other	0.5	23	102	17.5	16.1	43	3.9	17.6	14
Tot.	29.3	889	3960	22.1	18.4	68	269.4	1199.5	48

Fig. 9. Trestima report for the harvesting area 482

In particular, the Trestima report included the following data per each harvesting site which were used for the purpose of the research:

- area of a harvesting site, ha;
- basal area per tree species, m^2/ha;
- stems per tree species, pcs/ha;
- basal area-weighted mean diameter breast height per tree species, cm;
- basal area-weighted mean height, m;
- mean volume of growing stock per tree species, m^3/ha;
- total volume of growing stock per tree species, m^3; and
- share of logs, %.

  The timber volumes are given over bark. Pulpwood includes tree tops.

Net time of Trestima measurements accounted for 50 min for the both harvesting sites of appr. 6.3 ha, i.e., 20 min for the compartment 466 and 30 min for the compartment 482.

4.2.5 Preharvesting estimations by NOVIA's forest engineer

As mentioned above, NOVIA's forest engineer carried out the forest inventory with the view to obtain preharvesting data in January 2016. It resulted in a report with sufficient forest attributes in order to further sell the standing timber on the specified parts of the forest compartments 466 and 482.

For this purpose the forest engineer made a stand-wise forest inventory (SWFI) on the basis of ocular estimations, relascope measurements and his subjective judgment over the forest quality taking into account his previous overall professional experience, knowledge of the area, estimations of decay and other defects, and FMP data. The procedure of SWFI and calculations based on SWFI applied in this case were standard for similar tasks carried out in Finland and are described by Lehmonen (2015, p. 240-244).

In combining the results of the preharvest inventory into the invitation to submit offers with the view to buy standing timber, the forest engineer also used his knowledge about possible output of merchantable wood as well as about situation on the timber market existing at that time and possible behaviours of potential timber buyers.

The preharvesting estimations report provided by NOVIA contains the following data (see Fig. 10):

- area of harvesting sites, ha;
- volume of saw log per tree species, m^3 (MÄT – pine log, KUT – spruce log, KOT – birch log);
- volume of pulpwood per tree species, m^3 (MÄK – pine pulp, KUK – spruce pulp, KOK – birch pulp);
- volume of firewood, m^3 (titled as "ved"); and
- total merchantable volume, m^3.

The timber volumes are given over bark.

Område **Falkgölen** - uppskattad uttag, m^3

Figur	Avvslag	Areal, ha	MÄT	MÄK	KUT	KUK	KOT	KOK	ved	Totalt
466	Kalavv	1,9	130	65	50	40	0	10	5	**300**
482	Kalavv	4,4	320	180	180	190	10	20	10	**910**
Totalt		**6,3**	**450**	**245**	**230**	**230**	**10**	**30**	**15**	**1210**

Fig. 10. Preharvesting estimations by NOVIA's forest engineer

In these data NOVIA's forest engineer from the beginning subtracted the estimation of retention trees volume, which were defined and physically marked by him on the harvesting sites, as well as biotopes located within the boarders of the harvesting sites. Tree tops were not included either. The timber volumes are given over bark. The forest engineer meant pulpwood of worse quality by measuring energy wood (ved).

It is important to note that the forest engineer's pre-harvesting data include merchantable wood only, i.e. the volumes to be supposedly harvested, or forecast for factual recovery. These calculations are of subjective character and apart from all other mensuration methods they specifically aim at the actual harvesting results, though they are still of assumptions nature.

4.2.6 Harvesting report

In the framework of the study the major interest was to correlate the forest inventories by different mensuration methods to operationally obtained data at the harvesting stage. The measurement method of harvesting was cut-to-length. By the completion of the harvesting operations there was a report issued by the buyer (one of the largest timber-buying companies in Finland). The report contained data on the harvested volumes according to readings of the harvesting machine's head.

The harvested volumes of the study areas were thus registered on the spot by the logging machine, a PONSSE Ergo, and processed in MEKOGIS program. The measurement certificate (Mätningsintyg) was dated 31.05.2016 (Fig. 11).

Mätslag Slutmätning	Block 1 Prisgrupp 1	Kontraktsdatum 8.3.2016	Mätningsdatum 31.5.2016
Fastighet 710-431-0001-0624 Falkgölen			

Virkesslag	Kod	St	Netto	Enhet	EUR/Enhet	Totalt EU
Granmassaved	105		270,4	m3		
Tallmassaved	200		338,7	m3		
Gran, rötskadad	233		21,8	m3		
Björkmassaved, 3m	330		61,7	m3		
Tallstock	502		175,6	m3		
Tallstock	507		277,8	m3		
Granstock	629		233,2	m3		
Granstock, faner 52 dm	642		7,8	m3		
Björkstock, faner	741		3,0	m3		
Vrak-granmassa	991		23,1	m3		
Vrak-lövträdmassa	994		0,3	m3		
Tot Gagnvirke			1413,4	m3		

Nettomängd totalt
Gagnvirke 1413,4 m3

Fig. 11. The front page of the Measurements certificate

There was no available research on the subject of accuracy of PONSSE's heads except the one mentioned in paragraph 2 (Leitner et al., 2014). The producer does not give any more detailed information except stating that the harvester heads are "highly reliable on all types of sites" and demonstrate "precise measurement" (www.ponsse.com/products).

The harvesting report consisted of the following data for the two harvesting sites combined together in one block, i.e. without a differentiation per harvesting site:

- volume of pulpwood per tree species, m^3;
- volume of rotten wood per tree species, m^3;
- volume of pine saw log, m^3;
- volume of spruce saw log and plywood, m^3;
- volume of birch plywood, m^3;
- volume of defective wood (separately for spruce and broadleaved trees), m^3.
- number of stems per tree species, assortment-wise, pcs.

Per each tree species there were given lengths of cut logs, their respective diameters, number of pieces and volumes in cubic meters.

The harvesting report contains only the volumes of merchantable wood that the buyer has found acceptable and intends to pay for. The timber volumes are given over bark. The volume of tree tops is not included as well as the volume of retention, defected or other unsuited trees and parts of the trees left on the harvesting sites, i.e. which are not meant for sale or are not interesting for the purchase. Since there is a clear difference between theoretical and actual timber recovery (Peuhkurinen et al., 2008), the harvesting report represents the lowest possible figures for the total standing volume on the harvesting sites.

4.3 Methods

The data presented in the above-mentioned sources turned to be rather heterogeneous in their content, falling under no unified standard. This can be to a vast extent explained by the fact these data serve different purposes at different stages of the forest management lifecycle.

While the FMP mostly is to give an outlook to a forest owner and a forest engineer about the state of the forest, to estimate key forest state indicators and to plan optimal silvicultural operations, ALS in its turn serves to support forest management planning in a large scale as well as locally, providing in theory accurate data. Trestima is an inventory tool, which can be applied as a field sampling tool at large scale forest inventories, forest management planning on a local level as well as for a preharvesting inventory.

The key feature for Trestima, FMP and ALS is that they objectively calculate the volumes for these areas and do not imply any quality assessment of the standing volumes. The ALS does not give log/pulp breakdown estimations, whereas Trestima and FMP give their own specific averaged assessments on the log share per tree species for the whole area. Moreover, the resulting standing volume is total for the area, including tree tops and possible retention trees.

Preharvesting inventory performed by a forest engineer on the contrary is meant to deliver some realistic estimates of possible yield to proceed with sales. It gives the volumes per tree species without retention trees volume and tops and is based on the quality predictions. In this case it was calculated by a professional forest engineer with the knowledge of the current timber market situation in the region. The meaning of his estimation was to form an invitation to possible buyers, where the data were also presented bearing in mind to avoid higher expectations and make sales effective. The ground for this kind of assessment was personal experience, knowledge of the harvesting plot, ALS and FMP documents availability. The forest engineer's preharvesting estimations are of subjective character.

The harvesting report serves owner-buyer relations at the stage, when the volume is forwarded to a roadside, expenses were incurred and payments to be done for a specific work performed and factual volumes delivered. These volumes are calculated by a harvesting machine, outgoing from the harvester's operator decisions basing on the contract with the buyer and the actual state of each tree. The results exclude tree tops and the retention trees left on the area, the given log/pulp breakdown is done for the commercial task.

In the course of the study basing on the prior visual inspections and survey it was assumed that the defects were minimal and the bucking was effectively made and measured with the help of the logging machine.

In that regard, in order to compare the results of Trestima measurements, ALS and FMP data with the harvested volumes and the forest engineer's estimations, it was necessary to transform them into a common basis. The principle task was to make all the timber volume data obtained from the different sources actualized to the period of harvesting (2016), systematized by species as well as types of merchantable wood according to the harvesting report (i.e., saw log and pulpwood). All measurements were to be made free from retention trees and tree tops volumes. On top of that, calculations and comparisons of the key forest attributes such as mean diameter, mean height, basal area and number of stems were also done.

The processing approach per data source is described below.

4.3.1 Calculation of volumes of retention trees

The pre-harvesting forest inventory performed by NOVIA's forest engineer and consequently the harvesting results did not include retention trees. At the pre-harvesting inventory such trees were marked with tape.

Considering that the retention trees had not been not enumerated and calculated separately, it was necessary to measure them after the harvesting in order to further update all the rest data used at comparison. Examples of the retention trees left after the harvesting are shown on the Fig. 12 and Fig. 13.

Fig. 12. Example of retention trees left on the harvesting site (compartment 466)

Fig. 13. Example of retention trees left on the harvesting site (compartment 482)

The retention trees were measured by complete enumeration, detecting species, measuring height and diameter at breast height of each individual tree. The work was performed in September 2016.

All in all, 37 retention trees of the harvesting site 466 and 130 trees of the harvesting site 482 were measured. According to Laasasenaho's volume equations per each tree species (1982) the volume for every retention tree was calculated with the help of Excel.

The statistics on the retention trees are presented in the Table 1. Raw data on the retention trees are presented in Annex 3.

Table 1. *Generalized retention trees statistics*

Harvesting site	Species	Quantity of trees, pcs	Diameter, cm	Height, m	Volumes, m^3
Compartment 466	Pine	17	14.5-45	10-23	0.09-1.3
	spruce	16	9-34	7-22	0.03-0.87
	birch	1	13	9	0.06
	aspen	2	30, 48	18, 16	0.53, 0.97
	alder	1	31	17	0.52
Compartment 482	Pine	54	9-48	6-20	0.03-1.61
	spruce	61	8-20	5-18	0.01-0.28
	birch	14	12-45	11-21	0.07-1.13
	aspen	1	48	22	1.38

4.3.2 Actualization of the forest attributes per data source to the harvesting sites size and harvesting date

Forest Management Plan data

Originally, the FMP data were given for each whole forest compartment (see Fig. 3), whereas the areas of the harvesting sites were smaller. In that regard, the FMP volumes for each species for each harvesting site had to be recalculated applying the sizes of the harvesting sites.

At the same time, the original data of the FMP were actual to the date of 2014. For the purpose of comparability, the FMP volumes had to be actualized using a forest increment attribute stated in FMP for each harvesting site per tree species, taking into account its age classes if such were present. E.g., there were listed two age classes of pine on the compartment 466: of 110 years with 706 m^3/compartment and of 210 years with 259 m^3/compartment. These two classes had different increment indicated by FMP, which was taken into account while actualizing.

As the forest increment attribute was given for a total growing volume per species without differentiating between timber assortments (log and pulpwood), a share of such an assortment in the total volume to the moment of 2014 was taken into consideration too (see Eq. 1). This straightforward method was admitted for application due to the fact that the forest stands in the study were mature.

$$V_{FMP\ hs\ 2016\ i\ j} = (V_{mean\ FMP\ fc\ 2014\ i\ j} + N * R_{FMP\ 2014\ i\ j} * FI_i) * S_{hs} \qquad \text{(Eq. 1)},$$

where:

$V_{FMP\ hs\ 2016\ i\ j}$ - a volume of growing stock of a tree species age class *(i)* of an assortment *(j)* in 2016 at a harvesting site for FMP calculations, m^3;

$V_{mean\ FMP\ fc\ 2014\ i\ j}$ - a mean volume of a tree species age class *(i)* of an assortment *(j)* for a forest compartment (*fc*) in 2014 according to FMP, m^3/ha;

N – a number of growth seasons since the date of FMP till the date of harvesting;

$R_{FMP\ 2014\ j\ i}$ – a share of an assortment *(j)* in the volume $V_{mean\ FMP\ fc\ 2014\ i}$ of a tree species age class *(i)* in 2014 according to FMP;

FI_i – a forest increment of a tree species age class *(i)* according to FMP, m^3/ha/year;

S_{hs} - an area of a harvesting site, hectares.

The number of counted growth seasons was 2 (two), i.e. 2014 and 2015. Summarized volumes of tree species age classes gave volumes per tree species. Summarized volume of each assortment per tree species resulted in volumes of log and pulp per tree species. The calculations resulted in volumes per tree species and per assortments totally and for each harvesting sites.

Airborne Laser Scanning Data

ALS data were received in the form of a vector file grid (see par. 2.4.4). In that regard, the ALS data were cropped applying the shapes of the harvesting sites. That was done using standard functionality of the free GIS software qgis version 2.12.0 for vector data processing (see Fig. 14). The parameters were calculated using the ALS estimates for all the estimation units (grid cells) separately and treating the stand-level distribution as a combination of the grid cell-level distributions of the stand. Thus, for the purpose of the study the ALS inventory data were used at the level of these two stands.

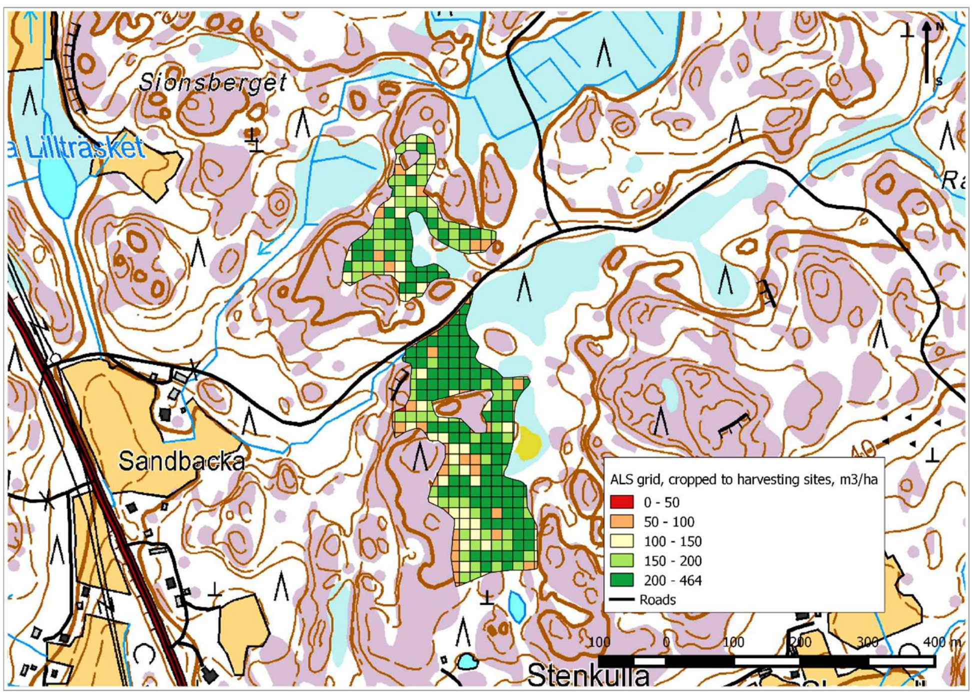


Fig. 14. ALS grid - cropped down to the harvesting sites shape

However, as after the cropping some cells of the grid lost their original shape, the volumes per each entire harvesting site had to be recalculated weighing a volume attribute of each cell with a cell area.

Similarly to the volumes, at calculating BA-weighted mean diameter and height for each entire harvesting site the respective attributes of each cell were weighted by a cell area and simultaneously a forest BA.

Next, as the ALS data were actual to the date of 2014, similarly to FMP they were updated to 2016 (see Eq. 2). The major difference being that ALS did not contain data on timber assortments and age classes, i.e. all the processing concerned only total volumes per tree species. The forest increment was taken from FMP, as ALS does not contain one. For ALS calculations it was counted as weighted average based on data of forest increments for age classes per respective tree species.

$$V_{ALS\ hs\ 2016\ i} = V_{mean\ ALS\ hs\ 2014\ i} + N_j * FIW_i \qquad \text{(Eq. 2),}$$

where:

$V_{ALS\ hs\ 2016\ i}$ - a volume of a growing stock of a tree species *(i)* in 2016 at a harvesting site for ALS calculations, m^3;

$V_{mean\ ALS\ hs\ 2014\ i}$ - a mean volume of a tree species *(i)* for a forest compartment in 2014 according to ALS, m^3/ha;

N – a number of growth seasons since the date of ALS till the date of harvesting; and

FIW_i – a weighted average forest increment of a tree species *(i)* according to FMP, m^3/ha/year.

The number of growth seasons equalled to 2 (two).

Estimations of Trestima and NOVIA's forest engineer

Since Trestima's and the forest engineer's inventories took place in 2016, the data of both sources were valid to the period of 2016. Any actualization with respect to the harvesting sites' areas and harvesting date was needless.

4.3.3 Subtraction of the tree tops volumes and the retention trees volumes

As stated above, the retention trees were left standing on the harvesting sites. Hence, as they were a part of such data as FMP, ALS and Trestima, they had to be subtracted from these data sources.

Volumes of the retention trees were divided into the following 3 (three) components: saw log, pulpwood and tree tops (see Table 2 and 3). For each individual retention tree they were respectively calculated as follows:

- tree volume (m^3), using models of Laasasenaho (1982) based on the measured diameter breast height and height of an individual tree;
- volume of saw log (m^3) based on diameter breast height and height of an individual tree according to the tables of volume distribution for log and pulp stems (Kilkki, 1989);
- volume of tree tops (m^3) based on diameter breast height of an individual tree according to the tables of volume per cent distribution (Kilkki, 1989);
- volume of pulpwood (m^3) – as a mathematical difference of the tree volume, log volume and volume of tree top.

The need to determine other tree species (i.e. other broadleaved than birch) was stipulated by the fact that Trestima detects broadleaved tree species separately.

Table 2. *Retention trees volumes (compartment 466)*

Tree species 466	Volume, m^3	Saw log, m^3	Pulpwood, m^3	Tree tops, m^3
Total pine	11,37	9,99	1,26	0,13
Total spruce	3,46	1,89	1,51	0,06
Total birch	0,06	0,01	0,05	0,01
Total other (aspen, alder)	2,02	1,37	0,62	0,02
TOTAL	**16,91**	**13,26**	**3,43**	**0,21**

Table 3. *Retention trees volumes (compartment 482)*

Tree species 482	Volume, m^3	Saw log, m^3	Pulpwood, m^3	Tree tops, m^3
Total pine	22,93	18,81	3,83	0,29
Total spruce	4,61	0,52	3,79	0,30
Total birch	5,55	3,70	1,76	0,09
Total other (aspen)	1,38	1,12	0,24	0,01
TOTAL	**34,47**	**24,16**	**9,62**	**0,69**

Trestima's data indicated log share per each tree species per harvesting site in its reports. The volume apart from the log share constituted pulpwood and tree tops volume. FMP's log and pulp volumes were differentiated by the plan for every forest compartment. ALS, as it does not contain any estimations on saw log and pulp volumes, undergone a slightly different processing. At all consequent steps of the data processing ALS merchantable wood volumes were taken as a whole. i.e., saw log and pulpwood together.

The tree tops volumes for ALS, FMP and Trestima measurements were estimated separately using the models of volume distribution (Kilkki, 1989), with respect to each data source's basal area-weighted mean diameter and basal area-weighted mean height.

At the next step, the tree tops calculated for every mensuration method were excluded, so that only saw log part and pulpwood for FMP and Trestima and saw log and pulpwood as a whole for ALS were left.

Finally, corresponding volumes of the retention trees for saw log and pulpwood were subtracted from respective volumes of FMP, ALS and Trestima. At the end of these calculations there were the obtained theoretical estimates for the usable trunk part for all of the three methods of the forest inventory.

4.3.4 Data comparison

The resulting data, prepared as described in par. 4.3.1–4.3.3, were further compared. The comparison were performed for the following parameters:

- Weighted average basic forest attributes contained in Trestima, ALS and FMP measurements (average weighted volume m^3 per ha, diameter BH cm, number of stems per ha, basal area m^2 per ha, height m). The comparison is done per tree species and per each harvesting site in order to consider the measurement methods divergences in composition of the final results.
- The number of stems calculated by Trestima, ALS and FMP as compared to the actual harvesting results per tree species.
- Volumes in m^3 per harvesting site per each tree species (pine, spruce, deciduous), per each tree species totally, per each harvesting site separately and for the whole harvested area. The comparison is done between Trestima, ALS and FMP measurements of the standing forest, preharvesting estimations of the forest engineer and commercially harvested volumes.
- The estimations of saw log (m^3) and its share (%) by Trestima, FMP and the forest engineer totally and per harvesting sites are compared to the actual harvested saw log.

Due to the absence of statistical variance of the results obtained in the course of this study, a statistical analysis was not performed. In other words, the results from only two harvesting areas situated close to each other, with validation data as one harvesting block were impossible to generalize.

5 Results

In order to observe and better understand the grounds for timber volume estimations done by the measurement methods in the study, the basic forest attributes given by Trestima, ALS and FMP are considered in detail and compared. Subsequently, there were parameters to be compared with the actual harvested data as per harvesting report, i.e., stem number and timber volumes estimations per harvesting site and per tree species. Separately, it is of benefit to investigate the predicted share of saw log and its correspondence to the real commercial log-and-pulp breakdown. In conclusion, there is a presented accuracy visualisation with the view to determine the method that gave the closest estimations to the harvesting results in the past preharvesting situation.

5.1 Basic forest attributes derived from Trestima, ALS and FMP data

The basic forest attributes per tree species per each harvesting area are presented in the Table 4 and were calculated as follows. All Trestima basic attributes were delivered in the corresponding report as weighted averages as the result of the forest inventory. The FMP also contained the forest attributes, however, two were recalculated as weighted average (D was stem number-weighted and H was BA-weighted). The ALS forest attributes data were BA-weighted.

ALS and FMP parameters were derived from 2014. There were no tools available to calculate growth for two seasons for such attributes as D and BA. Taking into account that the forest stands were mature and over-mature on both of the compartments, the two-seasonal growth in this case may be neglected.

Despite the fact that cumulative data by all the three measurement methods for both harvesting sites may show quite similar comparable total volumes, the Table 4, where the data are divided by cutting sites per tree species, shows as if there are different forests described by Trestima, ALS and FMP. The different forest attributes produced by the methods may finally make technical and economical differences in terms of forest management operations planning and sales.

Table 4. *The basic forest attributes derived from Trestima, ALS and FMP measurements*

Tree species, area	Average-weighted parameters	TRESTIMA	ALS	FMP
Pine, 466	Volume, m^3/ha	108,1	121,2	198,0
	Diameter (BH), cm	22,1	24,0	28,9
	Number of stems/ha	307	451	360
	Basal area, m^2/ha	11,7	14,7	22,0
	Height, m	18,2	17,6	19,3
Spruce, 466	Volume, m^3/ha	94,0	52,5	27,0
	Diameter (BH), cm	15,3	22,2	23,6
	Number of stems/ha	637	277	140
	Basal area, m^2/ha	11,8	6,2	5,0
	Height, m	14,1	17,7	14,2
Decidious, 466	Volume, m^3/ha	4,5	6,9	-
	Diameter (BH), cm	15,6	16,3	-
	Number of stems/ha	35	96	-
	Basal area, m^2/ha	0,7	1,0	-
	Height, m	15,4	15,28	-
Total 466	Number of stems/ha	**979**	**815**	**500**
	Basal area, m^2/ha	**24,2**	**21,9**	**27,0**
	Volume, m^3/ha	**206,6**	**181,2**	**225,0**
Pine, 482	Volume, m^3/ha	156,3	149,0	120,0
	Diameter (BH), cm	26,7	26,3	39,0
	Number of stems/ha	278	435	90
	Basal area, m^2/ha	15,5	16,6	11,0
	Height, m	20,9	19,1	25,0
Spruce, 482	Volume, m^3/ha	97,5	68,1	135,0
	Diameter (BH), cm	16,7	21,5	24,8
	Number of stems/ha	536	390	330
	Basal area, m^2/ha	11,7	7,8	15,0
	Height, m	15,1	18,2	20,8
Decidious, 482	Volume, m^3/ha	15,5	7,6	7,0
	Diameter (BH), cm	19,1	17,3	41,0
	Number of stems/ha	75	86	10
	Basal area, m^2/ha	2,1	1,0	1,0
	Height, m	17,6	16,9	25,0
Total 482	Number of stems/ha	**889**	**911**	**430**
	Basal area, m^2/ha	**29,3**	**25,3**	**27,0**
	Volume, m^3/ha	**269,3**	**224,6**	**262,0**

E.g., the forest attributes for harvesting site of the compartment 466 by FMP reveal dense pine forest with high growing stock of close to 200 m^3/ha with a large average diameter of 28.9 cm, which is 5–7 cm wider than estimated by Trestima and ALS. FMP also shows that within the harvesting site there is a small admixture of spruce also of a large average diameter and does not give any estimations of deciduous trees.

At the very same time, Trestima and ALS show nearly twice as less volume of pine on the area 466 compared to FMP, as well as twice as little BA for Trestima and 1.5 times smaller BA for ALS. Trestima estimates pine as 0.6 m higher than ALS. In general, at this harvesting site 466 pine volumes shown by Trestima and ALS are quite close to each other, though ALS estimates number of stems to be 1.5 times greater.

Spruce on the harvesting area 466 is described by the three systems in absolutely different ways. Volumes and number of trees differ greatly. The diameters are closer between ALS and FMP and override Trestima's diameters by 7–8 cm. ALS, being technically quite an accurate method in estimating heights, assesses spruce height by 3 m higher (at 17.7 m) than Trestima and FMP. Here Trestima clearly outlies the other two methods, showing higher volumes and number of trees, though lower and thinner.

Such Trestima's observations may be partly proved by the terrestrial images (see Annex 2 Part 1), from where it is visible that spruce can be met almost in all the parts of the harvesting site with an average diameter less than the diameter of pine, along the planned route, evenly covering the area (see Fig. 8).

Heights and diameters of deciduous trees on the harvesting area 466 are the same for Trestima and ALS, whereas the stem number by ALS is 96 against 35, estimated fewer by Trestima. This results in different basal areas and volumes.

Results from the lower-level comparison show that FMP may overestimate pine and underestimate spruce on harvesting area 466. Trestima and ALS were quite close to each other in estimating pine volumes. Spruce on the harvesting area 466 was the most controversial object of estimation having generally less volume than pine. While Trestima shows that its volumes of spruce and pine may with some tolerance be compared to each other, the other two methods show clearly pine-dominated area.

Concerning harvesting site 482, the difference in pine volume is not that substantial as per the same tree species on the area 466 (here the FMP data show 120 m^3/ha versus Trestima and ALS - 156 and 149 m^3/ha). However, the pine forest by FMP is taller by 5–6 meters, very sparse with 90 stems/ha and of a very large diameter (BA = 11 m^2/ha, D = 39 cm). Respective attributes of Trestima and ALS demonstrate lower trees (21 and 19 m) but of higher standing trees density (BA = 15.5 and 16.6 m^2/ha), with smaller similar diameters both around 26 cm. The difference in pine forest between Trestima and ALS is again in stem number (278 for Trestima against 435 for ALS) and, as mentioned above, almost 2 m in height "seen" higher by Trestima.

Volume of spruce on the harvesting area 482 was estimated by FMP at 135 m^3/ha, which is almost twice as higher than ALS and 1.4 times higher than estimated by Trestima. The diameter indicated in FMP constituted as much as 24.8 cm, compared to 21.5 cm by ALS and 16.7 cm by Trestima. The number of trees, estimated by FMP per ha, was the smallest and 1.6 times less than the respective 536 trees given by Trestima. The height was also greater than the other two parameters of ALS and Trestima by 2–5 m.

Spruce on the area 482, as "seen" by Trestima, was 5 cm thinner in DBH and 3 m lower in height than estimated by ALS, however there were 1.4 times more spruce stems than counted by ALS.

Combining the analyses of FMP's performance over the two harvesting areas, it should be noted that FMP measurements outstood in every case per each tree species with no revealed coherence. FMP's volume of pine was the greatest among the others on area 466 and the minimal among the rest on the harvesting area 482. On the contrary, volume of spruce was the least on area 466 and the highest among the three on this area 482. This double mutually complementary misevaluations resulted, however, in total volumes per harvesting areas not so substantially differing from the other two. In case of the harvesting area 466, the total volume exceeded only by ca. 20 m^3/ha that of Trestima's 202 m^3/ha.

On both harvesting areas 466 and 482 Trestima and ALS estimated volumes of pine close to each other. However, in both cases ALS overestimated number of trees by 1.5 times compared to Trestima. Height parameter measured by Trestima was in both cases greater than that of ALS by 0.5 – 1.5 m. Trestima's diameter was either the same or 2 cm less. These discrepancies form, however, similar resulting volumes. Fig. 15 illustrates the different perceptions of pine trees on both harvesting areas by the three measurement methods.

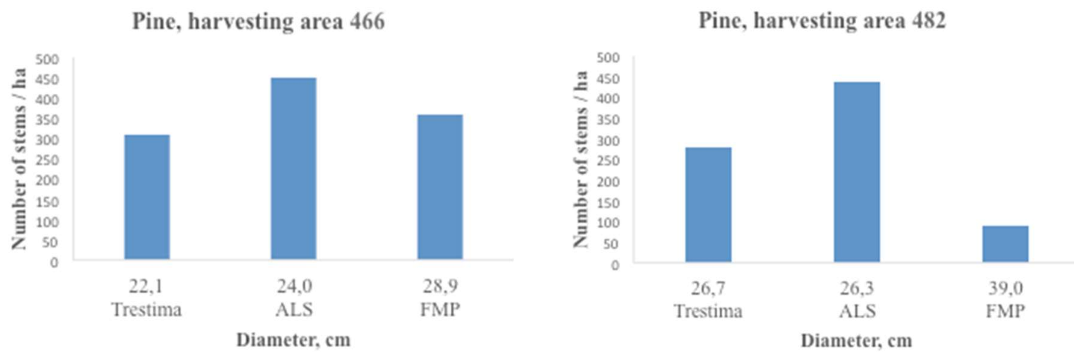


Fig. 15. Diameters and number of stems for pine calculated by Trestima, ALS and FMP.

As for estimations of spruce on the harvesting areas 466 and 482, in both cases heights of spruce by ALS were 3 m larger than by Trestima, either as ALS diameter was also greater by 5–7 cm than Trestima's corresponding measurements for spruce on both areas. However, number of stems was higher for Trestima at the range of 1.4–2.3 times than ALS, and finally volumes estimated by Trestima were 1.5–1.7 times greater, than by ALS. Trestima also overestimated stem number as compared to the actual harvested result.

In other words, in both cases ALS "saw" spruce only as much thicker and higher, in much fewer numbers (by 1 265 trees) than Trestima and by 692 trees less than the actual harvested stem number. Fig. 16 illustrates the different perceptions of spruce trees on both harvesting areas by the three measurement methods.

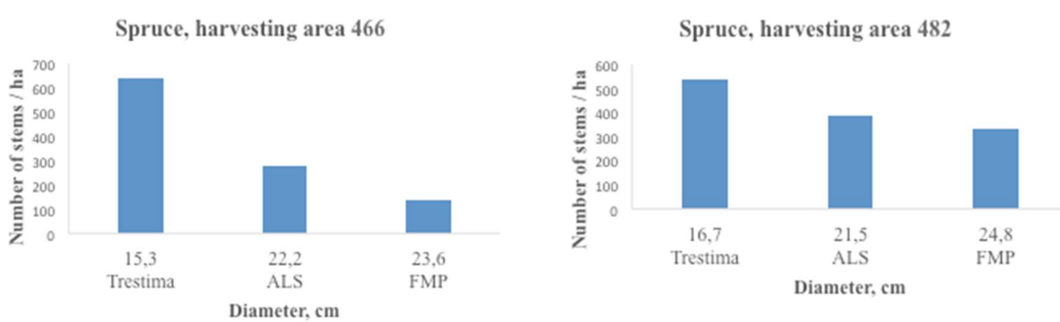


Fig. 16. Diameters and number of stems for spruce calculated by Trestima, ALS and FMP.

The actual harvested results do not contain the basic forest attributes; therefore, it was not possible to validate the above-considered measurements of Trestima, ALS and FMP by them. The essential aim of this paragraph was to investigate the contents of the raw data being the basis for further comparison of predicted volumes to the actual harvested volumes, in order to understand the nature of deviations if such occur.

5.2 Number of stems calculated by Trestima, ALS and FMP data, validated by the actual harvesting results

Species-specific stem number is one of the forest attributes that are important in the course of preharvest measurements and for forest management as a whole. It is one of the structural characteristics significant for silvicultural activity, wood procurement cost accounting and for “stem-pricing system” in timber sale. In one of its modes Trestima calculates timber volumes on the basis of heights paired with DBH per number of trees. Besides, an accurate stem number is a very good checking parameter for the harvesting activity, in order to receive evidence that all trees except for retention ones are accepted, measured and transported from the harvesting site.

This study provided substantial data sufficient to carry out comparison of predicted stem numbers by the three measurement systems with the actually harvested number of stems indicated in the harvesting report (see Table 5). Since the report contains the data for both harvesting areas as solid, the comparison was possible tree species-wise only.

Trestima and FMP stem numbers were calculated based on the stems per ha according to the sizes of harvesting areas, namely 1.9 and 4.4 ha. ALS data were taken as a sum of corresponding attributes per all grid cells of the harvesting areas. Stem numbers exclude retention trees.

Table 5. *Stem number per tree species, calculated by Trestima, ALS and FMP as compared to actual harvested results, pcs.*

N stems, area	TRESTIMA	ALS	FMP	Harvesting results
Pine, 466	566	901	667	
Pine, 482	1169	1886	342	
Total pine	**1736**	**2787**	**1009**	**1739**
Spruce, 466	1194	548	250	
Spruce, 482	2297	1679	1391	
Total spruce	**3492**	**2227**	**1641**	**2919**
Deciduous, 466	63	92	0	
Deciduous, 482	315	370	29	
Total deciduous	**378**	**462**	**29**	**501**
Total stem number	**5605**	**5476**	**2679**	**5159**

As it may be seen from the Table 5, the closest in estimating pine stem number was Trestima (only 3 stems fewer), as it was also closer to actual spruce stem numbers, though with the difference + 573 stems, i.e. by 19.6% more. It also overestimated the total number of stems by 8.6%.

ALS was the nearest to the actual results in predicting the total number of stems (overestimated by 6.1%), and the closest to deciduous trees harvesting result. For all that, it considerably overestimated pine (by 1050 stems) and underestimated spruce (by 690 stems).

FMP underestimated the number of stems in all the tree species categories and totally, altogether measuring almost twice as few stems than actually harvested.

The most noticeable here is the discrepancies arising over the total number of stems. ALS and Trestima both overestimated them by 300– 450 pcs, which in absolute figures may look like a big difference, however in relative values the difference constitutes +6.1% for ALS and +8.6% for Trestima. The reason might lie in this case, to a certain degree of probability, behind each measurement model of the estimation method.

However, the stem number is just one of the several basic attributes, insufficient alone to compare the methods, as well as to give a ground for defining the most accurate method or for defining possible sources of errors.

5.3 Comparison of predicted and harvested timber volumes

The timber volumes obtained in the course of Trestima and ALS measurements of the standing forest, as well as the data extracted from FMP, were reduced with the help of methods, described in the par. 4, into a format comparable with the actual harvesting results. The matching was done with the view of each harvesting site per tree species (pine, spruce, deciduous) and totally for the whole harvested area. The complete comparison data are placed in Annex 1.

The comparison is done in absolute values between Trestima, ALS and FMP measurements with commercially harvested volumes. Preharvesting estimations of the forest engineer are also taken into account as a subjective expert assessment as opposed to the estimations done by the three measurement systems based on more objective approaches.

In this study the comparison is done with the view to observe the method giving closest absolute result to the harvested volume. Regarding the general assessment of the measurements quality, the official document “Suomen Metsäkeskuksen metsävaratiedon laatuseloste" (the Finnish Forestry Centre requirements to the quality of the forestry data) was taken as a reference (Suomen Metsäkeskus, 2016).

The required accuracy, applied both to the conventional ocular measurements and RS-based forest inventories, admit the total volume deviation of ± 20 per cent in eight cases out of ten for the stands at the age of commercial thinning or final felling. The document also pays attention to the fact that there may be allowed greater deviations in accuracy if separate uneven forest stands are measured, especially small in size, which may be quite complicated for RS-based analyses. In case of tree species separate measurements at the stand, the minimal accuracy requirements is to correctly define the dominant tree species of the forest stand (Suomen Metsäkeskus, 2016).

This provision for volume deviation of ± 20 per cent from the corresponding harvested volume was used in the study as one of the general quality indicators. The requirements to the basal area, diameters and heights could not be applied in the study due to the absence of the corresponding reference parameters in the commercial harvesting results.

5.3.1 Pine volume comparison

In estimating pine volumes all methods of measurements proved to be within the accuracy requirements. As it is seen from Table 6, Trestima, ALS and FMP gave quite similar total volumes to each other, however, Trestima estimated the total pine volume closer than all other measurement methods.

Table 6. *The comparison of total pine volume (the harvesting areas 466 and 482)*

Volume, m^3	Trestima	ALS	FMP	Forest engineer	Harvesting result
Pine, total	872,86	883,67	876,99	695,00	**792,10**

Due to the absence of harvesting data per each harvesting area it is impossible to see the deviations per compartments. However, it may be noticed from the chart (Fig. 17), that inner deviations between the three methods compensate each other at the total pine volume level. However, Trestima and ALS measurements are generally in line with each other. The forest engineer estimated pine on both compartments at the lowest level, 482 harvesting area the same as FMP, 462 harvesting area much close to Trestima (both using relascope as their basic measurement instrument).

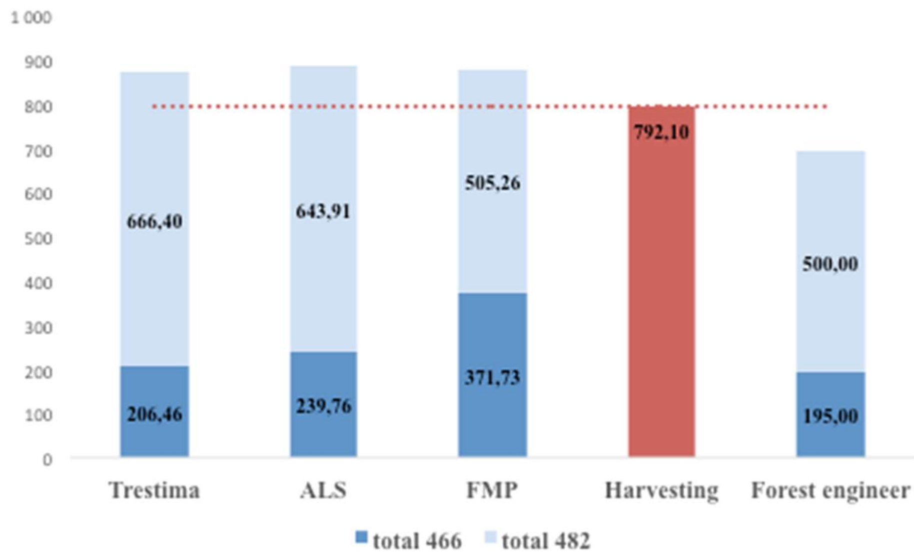


Fig. 17. Pine volumes by Trestima, ALS, FMP and Forest engineer against the Harvesting results.

5.3.2 Spruce volume comparison

Spruce turned out to be the most controversial object of estimation, presenting the widest spread of resulting values among all tree species or total volume in this study (Table 7). ALS fell out of accuracy requirements, underestimating the volume by 26%. The other three sources of estimations stand within ± 20% limit, with Trestima being the closest to the harvesting result. However, the Finnish Quality requirements allow poorer RS-based inventory's accuracy in case of estimating separate tree species.

Table 7. *The comparison of total spruce volume (the harvesting areas 466 and 482)*

Volume, m^3	Trestima	ALS	FMP	Forest engineer	Harvesting result
Spruce, total	599,02	*410,49*	645,50	460,00	**556,30**

There is also a considerable spread of estimations per compartments (see Fig. 18), with higher values for the harvesting area 466 by Trestima and the lowest by FMP. These two methods give also opposite polar estimations to the harvesting area 482. The forest engineer was closer in his estimations to ALS data, especially for the harvesting area 466, and they both underestimated spruce on the two areas. However, the forest engineer could in this way take into account the problem with root decay that was present in the region, and this fact was also supported by the harvesting report.

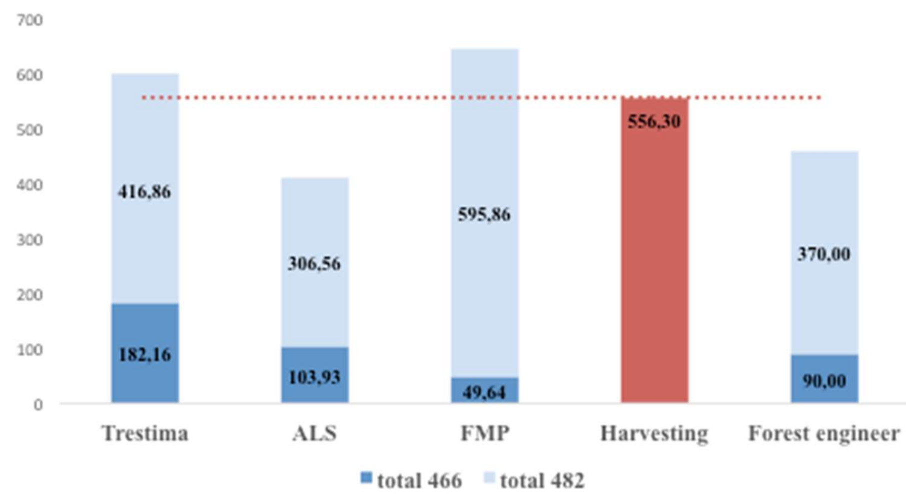


Fig. 18. Spruce volumes by Trestima, ALS, FMP and Forest engineer against the Harvesting results.

Based on the previous information on the stem number and forest attributes, it might be already here assumed that Trestima could in this case overestimate and ALS on the opposite could underestimate the presence of spruce. This supposition shall be considered in more detail in par. 6.

5.3.3 Deciduous trees volume comparison

The measurements of deciduous trees were specified by the fact that the notion “deciduous trees” was perceived by all the methods in different way. ALS estimated all of them as “lehtipuu” (broad-leaved) without specifying the tree species. FMP defined only “vårtbjörk” (European white birch), the forest engineer estimated ”björk” (birch). Trestima identified separately ”birch” and ”other” trees. Harvesting report indicated birch and broad-leaved trees separately in different tree species categories and assortments. It is also important to note, that among the assortments there was also birch plywood, which may be of a high separate value on the market.

By ocular examination of the areas 466 and 482 at the time of Trestima inventory there were detected not only birch, but also aspen and alder trees. A part of them were left as retention trees, at later stages measured and deducted from Trestima initial measurements of "other” trees category. However, this particular broad-leaved trees species identification allowed, e.g. by Trestima, may be of a principal meaning in case of deciduous trees stand inventory. For a birch-based plywood factory it makes difference, which broad-leaved tree species are detected and then harvested, as in that case only birch would be needed for plywood manufacturing.

Therefore, to take into account volumes of birch separately, as they have their own value, two comparisons were done, one is to compare the birch between the methods where it was marked out as birch, and the other to compare all deciduous trees measured on the harvested areas.

Birch volume comparison

Table 8. *The comparison of total birch volume (the harvesting areas 466 and 482)*

Volume, m^3	Trestima	ALS	FMP	Forest engineer	Harvesting result
Birch, total	52,86	-	*26,12*	*40,00*	**63,10**

Table 8 shows that Trestima gave the closest volume of birch to the harvesting result. ALS did not indicate the birch separately and therefore takes part only in the deciduous trees comparison. FMP and the forest engineer underestimated the volumes of birch, which theoretically fall out of the 20% accuracy limit, however the Quality requirements allow bigger discrepancies in case of tree species particular estimations, especially of minor values.

The distribution of volumes between the compartments (Fig. 19) demonstrates that Trestima and the forest engineer almost equally estimated birch on the harvesting area 466, however, their calculations regarding the harvesting area 482 differ from each other.

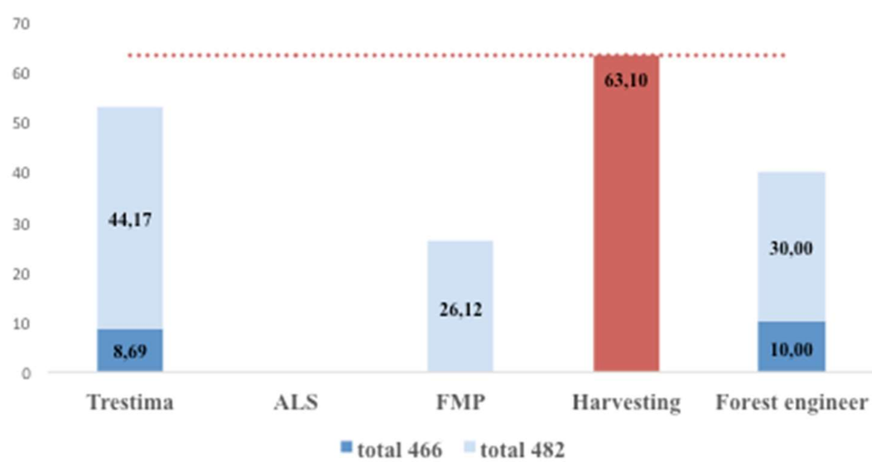


Fig. 19. Birch volumes by Trestima, ALS, FMP and Forest engineer against the Harvesting results.

Only Trestima found other types of deciduous trees. On the harvesting area 482 Trestima gave their volume at 16.20 m^3, whereas the harvesting report indicated broad-leaved pulpwood at 1.9 m^3. Here it may be noted, that the volumes of other broad-leaved trees were much overestimated by Trestima and obviously might have been misinterpreted with the birch on the area.

Total deciduous trees volume comparison

Table 9 presents the comparison of overall deciduous trees, measured by the three methods and estimated by the forest engineer. Here it may be noticed that Trestima gave the closest result to the actually harvested volumes, while the other methods and the forest engineer underestimated the volumes of broad-leaved trees, which might be allowed by the Quality requirements in the case of minor tree species on the smaller areas. FMP underestimated the volume of deciduous trees the most.

Table 9. *The comparison of total deciduous trees volume (the harvesting areas 466 and 482)*

Volume, m^3	Trestima	ALS	FMP	Forest engineer	Harvesting result
Deciduous, total	68,56	*38,52*	*26,12*	*40,00*	**65,00**

It should also be noted that in this case deciduous trees volumes might have been disregarded by FMP or the forest engineer, e.g., as they are only very minor part of the stand and do not bear the commercial sense in this case. The forest engineer also assessed the quality of deciduous trees and could assume in this way volumes of defected trees, which he deducted from his estimates. The harvesting report indeed showed that there were trees of worse quality, however, not that many.

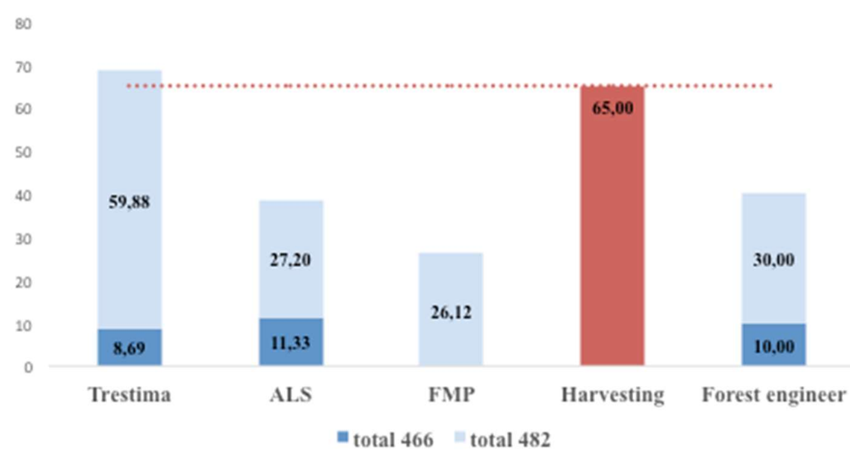


Fig. 20. Deciduous trees volumes by Trestima, ALS, FMP and Forest engineer against the Harvesting results.

The chart above (Fig. 20) illustrates that ALS, FMP and the forest engineer almost equally estimated all deciduous trees on the harvesting area 482 in volume, and Trestima, ALS and the forest engineer almost equally estimated the corresponding volumes for the harvesting area 466. However, in overall volumes Trestima estimated deciduous trees closest to the final harvested result.

Operational ALS-based inventories are quite often characterized by lacking information on minor species (Peuhkurinen, 2011), which might be also the case in this study. However, visual measurements could have given more evidence of the broad-leaved trees presence.

5.3.4 Total volume comparison

Table 9 summarizes the results over timber total volume estimations carried out by Trestima, ALS and FMP on the harvesting areas 466 and 482 and compares them to the preharvesting estimates of the forest engineer and actual harvested volumes. Despite the fact that Trestima stood the closest in estimating volumes per every tree species, it is the ALS that estimated the total volume on the harvesting areas 466 and 482 closer to the harvesting results.

ALS was quite close in estimating pine volume, however it considerably underestimated spruce and also underestimated deciduous trees. But at large, this resulted in smaller discrepancy in total volumes than the corresponding discrepancy for Trestima, which was made up from each surplus, though not sizeable, over actual harvested volume per every tree species.

Despite all its outlying in absolute values measurements, both greater and lower, FMP made up its final results at the same level as Trestima (only 9 m^3 more), which seems very ambiguous in the specific preharvesting situation. The forest engineer delivered the most pessimistic estimates, and in this case it was difficult to distinguish the manual measurements from the subjective assessments and current market personal perceptions.

Table 9. *The comparison of total volume (the harvesting areas 466 and 482)*

Volume, m^3	Trestima	ALS	FMP	Forest engineer	Harvesting result
Total, 466 and 482	1540,44	1332,68	1548,61	1210,00	**1413,40**

It should be principally stressed that estimations by all the methods fall within the accuracy limit for the volume measurements set up by the Finnish Quality requirements (± 20% of the volume). The total volume in view per hectare is displayed in Table 10.

Table 10. *The comparison of total volume per hectare*

Volume per ha, m^3	Trestima	ALS	FMP	Forest engineer	Harvesting result
6.3 ha (466 and 482)	244,51	211,54	245,81	192,06	**224,35**
Difference, m^3/ha	(+) 20,16	(-) 12,81	(+) 21,46	(-) 32,29	

Total volumes by each measurement method, including information per compartments, are illustrated on the chart below (Fig. 21).

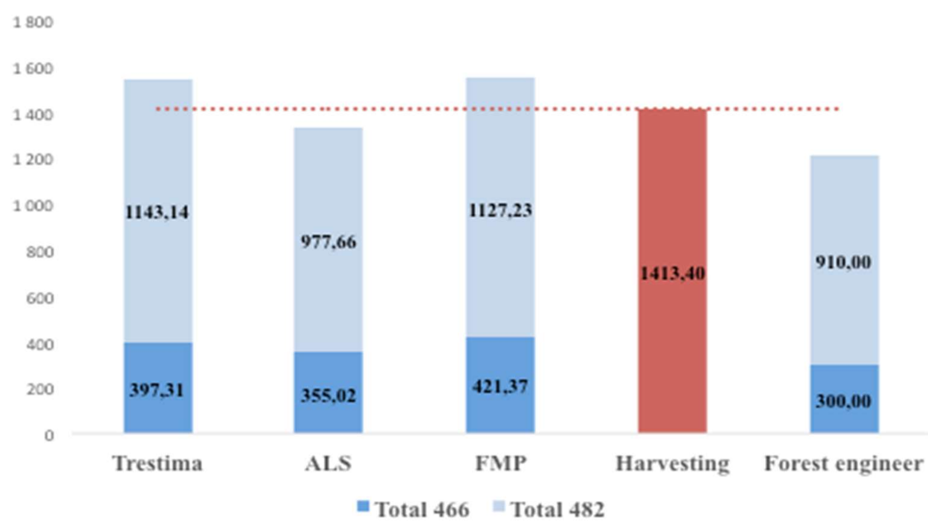


Fig. 21. Total volumes by Trestima, ALS, FMP and Forest engineer against the Harvesting results.

Generally, estimations of each harvesting area carried out by Trestima, ALS, FMP and the forest engineer, differ from each other. The only closest were Trestima and FMP in estimating volumes of the harvesting area 466 (with 16 m^3 difference). The most pessimistic for every compartment was the forest engineer, who was then followed by ALS predictions. Unfortunately, the harvesting report did not show the volume per compartments, which does not let draw the comparison in this case.

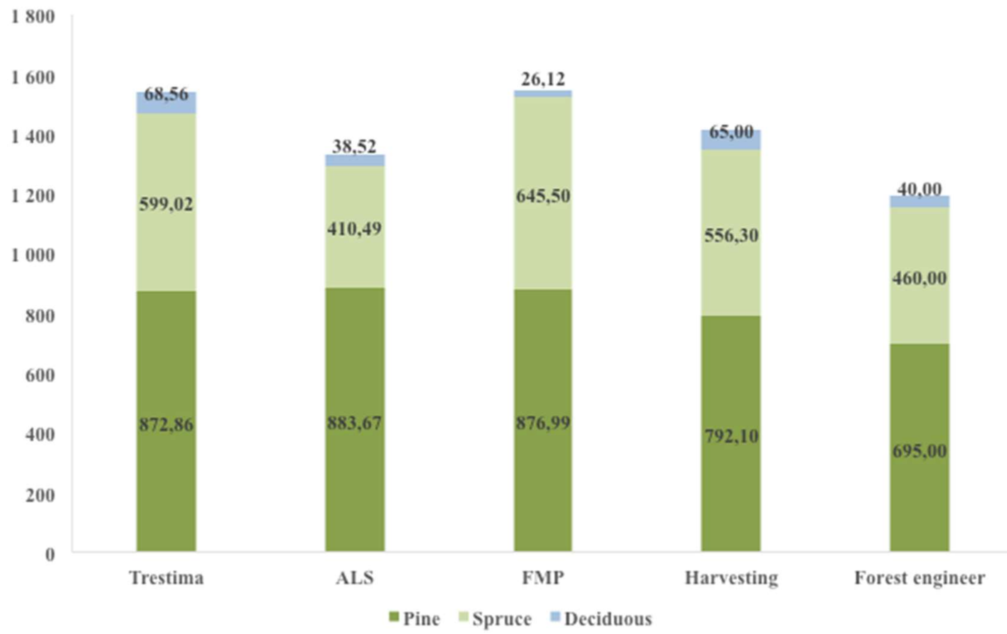


Fig. 22. Total volumes with tree species composition, estimated by Trestima, ALS, FMP and Forest engineer, and the Harvesting results.

Fig. 22 combines on the chart total volumes composed of tree species volumes. This illustrates the fact, that the pine, quite similarly assessed by the three methods, forms the common basis for the estimates, and finally they differ to the vast extent due to the discrepancies in spruce estimations. The methods also differ in deciduous trees volume, but it is responsible in this case only for 4% of the total volume (counted from the harvested results) and does not change the overall estimates in any considerable way.

All methods unanimously agree that pine was the dominating tree species, which is also supported by the harvesting results. In this context all methods fulfil also one of the general criteria listed in the Quality requirements, i.e. to correctly define the dominant tree species on smaller size areas within separate measurements of tree species.

Therefore, as conclusion it can be summarized that all methods generally meet the Quality requirements to the forestry data. Although ALS measurements underestimated spruce and deciduous trees above the 20% accuracy limit, according to the minimal provisions of the Quality requirements, as RS-based inventory it is allowed to produce the data with errors beyond the limit, provided that it correctly defines the dominant tree species on the individual areas, similar to the compartments under the study. However, it should be pointed out, that for the purpose of the preharvesting inventories such potential errors might have consequences for the forest owners due to the fact that ALS data need additional checking. So, ultimately there should be questions to the reliability of the ALS estimates of smaller individual areas, in line with the statements provided in par. 2.

5.4 Comparison of the predicted and harvested saw log volumes

As it has been already considered in the first two paragraphs of the study, in order to estimate the economic value of the timber, the forest owner need timber assortment volumes (Korhonen et al., 2008). And within the total timber volume the saw log share affects the forest owner's total income the most, since it is the most valuable timber assortment.

This type of comparison is meant to define the measurement method, which more accurately predicts the share of saw log, in order for the forest owner to compare the bids and make well-founded choice of a buyer. The general results of such comparison are indicated in Table 11, the detailed information on the log share per each compartment can be found in Annex 1. The ALS did not provide data on the log share, which made it impossible to use the received ALS data for the purpose of log/pulp breakdown analyses and comparison (see in more detail par. 4.2.3).

Table 11. *The comparison of total saw log volume per principal tree species*

Saw log volume, m^3	Trestima	ALS	FMP	Forest engineer	Harvesting result
Pine, total log	485,19	-	501,14	450,00	**453,40**
Spruce, total log	231,45	-	233,48	230,00	**251,90**
Total log	728,64	-	734,62	690,00	**708,30**

Considering the predictions made by Trestima, FMP and the forest engineer, with the previous knowledge of their divergent measurements, one can with interest state that these estimations are very close to each other and to the actually harvested saw log volume.

The pine saw log estimated by the forest engineer became utterly exact as harvested, with only 3 m^3 difference. Trestima overestimated it by 30 m^3 and FMP – by 50 m^3. The chart below illustrates the pine saw log and pulpwood estimations together with the actual harvested volumes (Fig. 23).

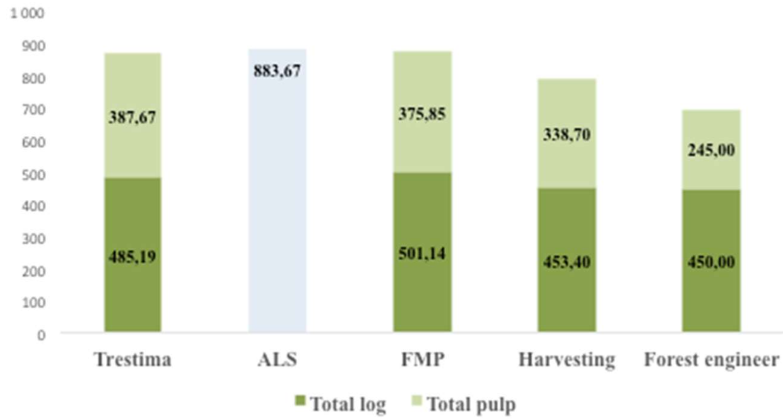


Fig. 23. Total pine volumes per timber assortments by Trestima, FMP and Forest engineer against the Harvesting results.

The ground for interest in this case is that the overall volumes of pine were estimated by these three sources quite differently: 872 - 876 m^3 by Trestima and FMP, and 695 m^3 by the forest engineer. The actual harvested pine volumes were in-between them, at the level of 792 m^3. However, the pine log volumes per compartment were again quite different, i.e. by Trestima – FMP – the forest engineer respectively for the harvesting area 466: 94 m^3 – 180 m^3 – 130 m^3; for the harvesting area 482: 390 m^3 – 320 m^3 – 320 m^3.

The total actual log percentage was 57%, which was the same as projected by FMP and 56% by Trestima. The forest engineer expected the pine saw log share at the rate of 65%.

The total spruce log is absolutely unanimously predicted and underestimated, though spruce log on the harvesting area 466 got estimated by Trestima, FMP and the forest engineer respectively as 67 m^3 – 8 m^3 – 50 m^3, and 164 m^3 – 225 m^3 – 180 m^3 on the harvesting area 482. The actual harvesting result of spruce saw log became 20 m^3 greater, the difference being only 3% of the whole spruce log volume. Spruce timber assortments predicted by Trestima, FMP and the forest engineer are illustrated on Fig. 24.

The total actual log percentage for spruce was 45%, at the same time Trestima projected this indicator at the rate of 39% and FMP at 36%, whereas the forest engineer expected the spruce saw log to be at the rate of 50%.

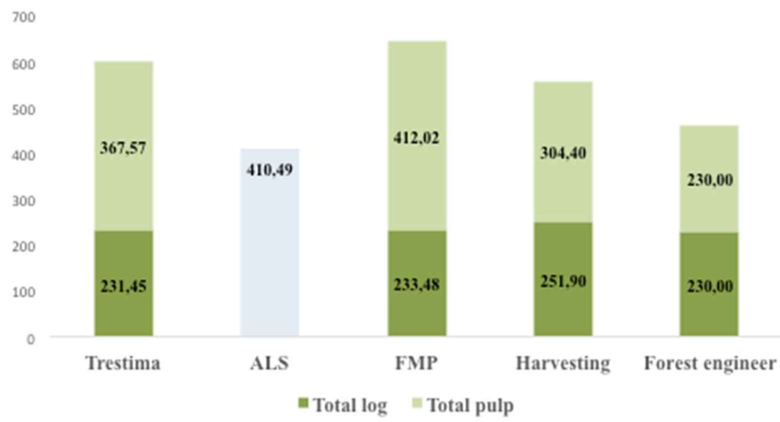


Fig. 24. Total spruce volumes per timber assortments by Trestima, FMP and Forest engineer against the Harvesting results.

Timber assortments predicted totally by Trestima, FMP and the forest engineer are illustrated on Fig. 25.

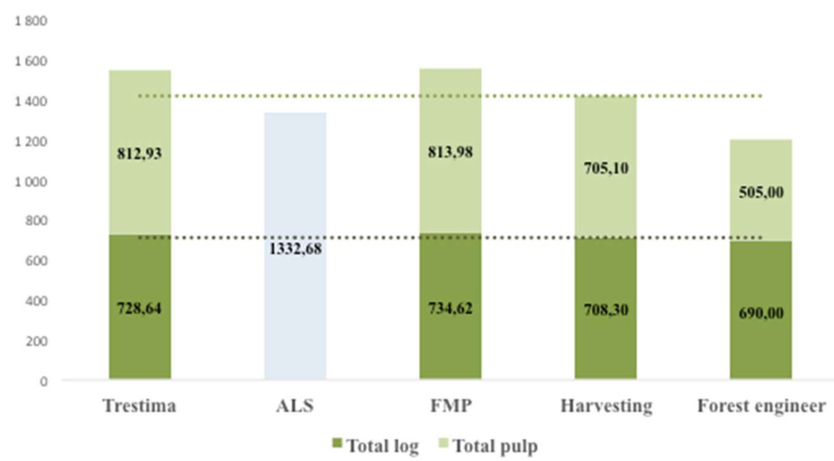


Fig. 25. Total volumes per timber assortments by Trestima, FMP and Forest engineer against the Harvesting results.

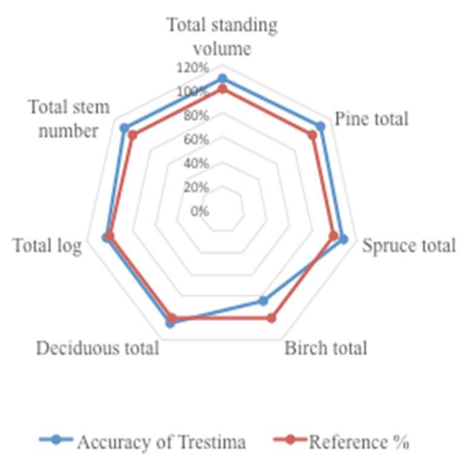
Totally, despite the divergences in log estimations per compartments and tree species, the forest engineer underestimated the saw log volumes approximately with the same relative difference 3% (- 18 m^3) as Trestima, which overestimated the saw log volumes by + 20 m^3. FMP overestimated the same way as Trestima, by + 26 m^3. One can notice that the saw log was predicted generally more accurately than the pulpwood, the assessment of which made bigger discrepancies as compared to the actually harvested pulpwood.

5.5 Visualisation of the measurement methods' accuracy

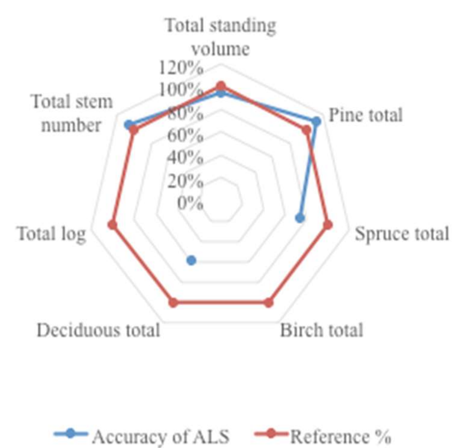
Knowing the raw data indicators and controversial estimates of some methods, it was impossible to determine the most accurate method on the basis of one criterion, i.e. absolute proximity to the total volumes. Besides, the purpose of the study considered the methods in the preharvesting situations with the view to examine in detail the information provided by the measurement methods in the specific preharvesting situation. The more information is provided to the forest owner, the more grounded decision he/she can take on the competitive market.

The goal of the visualization was to consider in aggregate all discrepancies in preharvest stand characteristics (stem number, total volume, tree-species volume and log percentage) and reveal the most informative method of the preharvest forest inventory giving the nearest estimations to the harvesting results, stand-level-wise, according to the corresponding information presented by the harvesting report.

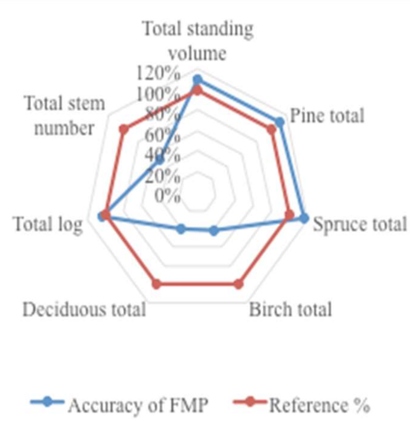
The accuracy of methods in this study has been visualised by means of a radar chart. It allows to examine relative values in multivariate comparisons and to define which observations are most similar to the reference data. The reference data here were the actual harvesting results and they were marked as the basic 100 % accuracy line. The accuracies of the measurement methods are illustrated on Fig. 26.



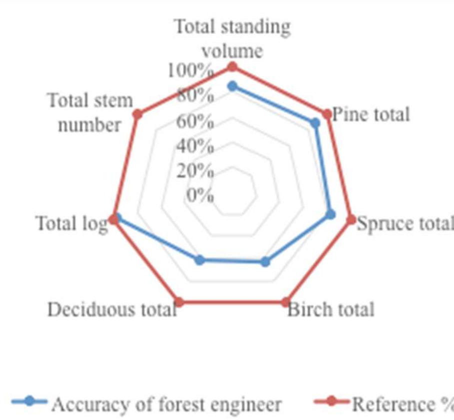
Accuracy of Trestima measurements



Accuracy of ALS measurements



Accuracy of FMP measurements



Accuracy of the forest engineer measurements

Fig. 26. The visualised accuracies of measurements by Trestima, ALS, FMP and Forest engineer.

The criteria were chosen according to the contents of the harvesting report, which were total standing volume, total volumes per tree species (pine, spruce, birch and deciduous separately), total log volume (as summarized saw log volumes per each tree species) and total stem number. The method that gives more accurate preharvesting information according to this set of criteria is considered to be the most effective to the forest owner, as it equips him/her with the necessary set of information for choosing a bid on a competitive market.

The criteria missing from this list is the presence of quality estimation of the stand. None of the methods available as a method for forest inventory to the forest owner provide so far such information. The forest engineer can take it into account with his personal subjective estimations. Trestima and FMP may also have it marked during the visit to the stand for the inventory purpose, though also subjectively. For ALS method it is not so realistic to attempt to estimate all the defects affecting the tree quality, although it is theoretically possible with higher requirements to the field plot samples and used models (Peuhkurinen, 2011).

In principle, it should be noted that all estimates produced by the three methods and by the forest engineer met the Finnish Quality Requirements to the forestry data (where there are no requirements to the stem number calculations and log share). It should be also pointed out that all the methods have their strengths and weaknesses discussed above. However, as it may be noticed from the charts (Fig. 26), the most accurate and full information available and necessary to the forest owner was in this study delivered by Trestima measurements.

FMP is also a very informative tool, which, however, in this case showed neither consistent raw data, i.e. forest attributes, nor accurate enough estimations per all tree species. ALS might be a very useful inventory tool on a bigger scale, which still needs adapting in order to be applied for the purpose of a stand-level inventory. Weaknesses, mentioned in the previous studies of ALS-based inventories, proved to be apparent also in the case of the study, i.e. species-specific analyses, especially on smaller areas. The forest engineer, having at his disposal various strata of information, might be influenced by subjective factors, which both can assist in the right assessment, as well as can interfere in the judgements (e.g., over- or underestimating in the case of quality, which can influence log share, etc.).

6 Discussion

It should be noted that all these three measurement methods considered in the study can't be named as clearly preharvesting, as they are means of ordinary forest inventory. However, they are often used as a basis for preharvesting estimates, especially in case of sale on the stump. Effective preharvesting decisions depend on the quality and quantity of the information delivered by the inventory. Even if models simulating factual recovery are used for the purpose of preharvesting estimations, they nevertheless require accurate input data (Peuhkurinen, 2011).

The present study considered the accuracy of the measurement methods that were available in the specific preharvesting situation, i.e. Forest management plan and ALS data, both obtained in 2014. Additionally, it was decided to use Trestima as a quick and available forest inventory tool in order to be able to compare the accuracy of the three estimation systems, i.e. based on stand-wise forest inventory, on remote-sensing and on a smart software solution, combining relascope principles and computing models.

In the first place, it should be stressed that all the measurement systems, including information in the harvesting report, turned out to be highly incompatible to each other. The attempt to transform the estimates to a comparable state was quite time-consuming and might have resulted in worse accuracies of the results obtained. One of the conclusions of the study is that compatibility of the forest inventories with the view to be compared to each other and to project harvesting volumes and incomes is beneficial to forest owners.

Analyzing the performance of FMP's measurement in this study and comparing it to the results of the previous research on SWFI accuracy, it might be confirmed that there was a reason to doubt the estimates of FMP, especially tree species-wise and compartment-wise. While ALS and Trestima were quite similar in their estimates of pine volume on both of the areas, FMP outlied in both cases in different directions in diameters, number of stems and heights. However, on the total volumes, both per dominant tree species and combined for both compartments, it gave estimates of the same order as the other two methods, ultimately showing total volume and total saw log volume unanimously with Trestima.

Judging based on only one source of the data it can lead to misperception of the real situation and wrong decision. E.g., if buyer has pine as targeted wood then taking FMP data alone one can make a conclusion that the harvesting site 466 is the best choice, however, all other available sources showed the opposite.

The higher tree diameters and heights of FMP can be explained by a tendency of a human to select larger basal median trees at sampling. From Table 4 it is noticeable that FMP operates diameters and heights of the values significantly exceeding the values of the same attributes by Trestima and ALS, concerning all harvesting sites and all species. That potential source of inaccuracy has been confirmed by Trestima (RusFor Consult, 2016) at Russian projects on large forest stands. At those projects field team tended to select a larger tree as so called “model” trees. Direct application of such Ds and Hs was normally leading to volumes’ overestimation.

However, the reasons for considerable deviations of FMP estimations for number of stems and basal area attributes stay unclear. The discrepant outlying basic attributes in all FMP parameters as compared to the other two systems may suggest, though, doubt in validity and soundness of FMP detailed measurements. One of the possible ways to support the validity of FMP is to use Trestima as means of the plan update.

At the same time it should be also noted that although the stand-level inventory method has several shortcomings, as discussed earlier, it is not likely to result in such gross errors in the estimation that would lead to utterly incorrect or economically unsound silvicultural treatments, since all stands are visited in the field and can be examined personally.

The information provided by ALS-based forest inventories has certain benefits over the field inventories. ALS data provide spatial information with reliable accuracy that can be further managed and analysed in geographical information systems. Various strata of information provide opportunities for modelling of related variables such as spatial, height and diameter distributions. In this study ALS was the most accurate method to predict total volume and total number of stems, but at the same time it was less accurate than Trestima species-wise.

However, in this study it was confirmed that application of ALS data for the purpose of stand-level preharvest inventory is complicated. The ALS data showed inaccuracies in predicting spruce volumes. The absence of inbuilt saw log and pulpwood volumes, as well as generalization of deciduous trees make it difficult to project the income. Thereby, the results of previous research regarding possible ALS inaccuracies of species-specific attributes estimations, especially on areas of smaller size, were also confirmed by this study. Tree quality characteristics are also missing from the ALS inventory, which can generally cause a significant effect on the actual recovery of the timber assortments.

There are no known theoretical limits for Trestima application, connected, e.g., to small diameter of measured trees, uneven stands or small areas (as for ALS method). In this study Trestima showed the most accurate estimates of pine stem number, spruce stem number, pine volume, spruce volume, deciduous and separately birch volume. It also showed very good results in log predictions.

However, Trestima tended to overestimate all the above-mentioned parameters, which became the ground for overestimation of total volumes and total stem number, whereas ALS got its under- and overestimated parameters compensated on the total level. The reason might lie behind the calculation model of each estimation method.

Trestima and ALS measured pine volumes generally with a very good correspondence to each other. According to the latest research done by Siipilehto et al. (2016), Trestima performed best at diameters and number of stems estimation, which might be referred to in this study as well. At the same time, on the basis of the previous research the high accuracy of height estimation by ALS has been confirmed, e.g., by Tuominen et al. (2014), who reported RMSE of 8-9% and by Yu et al. (2015) with respective RMSE 4.6–5.3%. Siipilehto et al. (2016) assessed accuracy (RMSE) of height estimation by Trestima at 14.6–16.5%. That can give evidence to the supposition that while predicting the number of pine stems and diameters quite accurately, Trestima overestimated the height (ALS showed 0.5–1.5 m lower), which resulted in higher pine volumes.

Spruce turned out to be the most controversial object of estimation, presenting the widest spread of resulting values than any other tree species or total volume. Basing on the information on the spruce stem number, Trestima could in this case overestimate and ALS on the opposite underestimated the presence of spruce. These discrepancies might arise out of, including but not limited to: a) errors in tree species identification (when part of spruce was recognized as pine, which is supported by far too great number of pine stems as compared to the harvested number); b) ALS did not capture by some reason the part of spruce trees of smaller diameters; c) set-ups for mathematic modelling and field sampling arrangements (in terms of similarity of used auxiliary and field data).

The additional difference in diameters (5–7 cm more for ALS “spruce”) can also suggest that the pre-mature spruces of above-mentioned diameter highly likely were not properly detected by ALS. This can be supported by the fact, that the Finnish Forestry Centre in its Quality requirements (2016) does not consider remote sensing to be sufficiently reliable in the case of, e.g., young stands, when such stands require additional inventory or supplement information based on various sources.

At the same time, Yu et al. (2015) in their study reported BA accuracy (RMSE) of 14.8–15.9% for ALS, whereas Siipilehto et al. (2016) reported the corresponding RMSE of 30.9–31.3% for Trestima. Consequently, Trestima may in this case overestimate on the contrary BA for spruce. However, these large deviations of RMSE might only suggest such a reason.

Volume is a derivative of such forest attributes as either pair "height and basal area" or pair "diameter and number of stems". In that regard, volume to a large extent depends on the basic attributes. However, under remote sensing volume is commonly estimated directly, i.e., based on volumes obtained from field sampling data.

Possible inaccuracies of ALS connected to the modelling can be explained by the fact that although theoretical studies of ALS demonstrate high enough accuracy of forest attributes estimation, the real situation for a particular site like Falkgölen might differ locally at each forest compartment. It means that, as the operational forest inventory using ALS or any other RS technique normally covers large areas, the actual field sampling can take place at some other, although very nearby located, area and at very similar forest but not the one like at Falkgölen. The local environmental and other specifics always differ a lot from site to site and cannot be taken into consideration by any even very complex estimation model or algorithm.

Inaccuracies of Trestima may hide also behind two aspects. The first is the method of fieldwork. Ideally, it is necessary to sample with Trestima over an entire site in order to obtain significant statistics. That will heavily influence the very initial attributes such as number of stems, diameter (including D distribution) and BA. Particularly, the fact that the spruce volumes were quite similar to harvesting results but the stem number was assessed greater may be the evidence of wrong diameter distribution. Second is estimation algorithms for forest attributes like height and volume, which are appropriate H(D) functions and allometric formulas for volume per species.

Trestima performed in this study efficient enough both in presenting accurate data within the limits set by the Finnish Quality recommendations to the forestry data, as well as presenting information according to the full set of criteria, established on the basis of the harvesting report. On the basis of accuracy visualization, it proved to be the most effective among the other considered methods in the preharvesting situation, supporting the results of the Siipilehto et al. study (2016).

This study also supports the conclusion made by Rybakov (2015) that Trestima demonstrates good prospects to be either a forest inventory tool and/or as a forest data validation tool, which could be used by forest engineers or forest owners at their regular measurements. However, despite this fact, it might be also pointed out on the basis of this research that Trestima needs further development and improvement.

Another interesting fact revealed by the study is that in many cases a deviation of one forest attribute was then compensated in the opposite direction at the next related forest attribute, which resulted in the situation that, e.g., mean volumes by different methods were situated in the close proximity one to another, especially that was the case for FMP.

Still more to mention is that according to the study, pine was estimated unanimously by the measurement methods as opposed to spruce, and saw log was estimated unanimously and more accurately than pulp wood, which is especially of interest taking into account polar measurements of basic forest attributes by the methods.

The forest engineer who had both FMP and ALS data at his disposal was very independent in producing his estimations. Preharvesting inventory performed by him, generally, gave lower estimations than actual harvesting results, on one side in order to deliver realistic estimates to proceed with sales, on the other side the forest engineer was very accurate in predicting the saw log volume, especially per pine, with only 3 m^3 difference. The probable reason why the engineer was independent in his estimates might be that the inventory tools available to him were found by him insufficient or unsatisfactory, apart from the strategy to show the lower volumes but with higher accuracy.

In general, the development of the various measurement systems may question the role of a forest engineer in future, provided that a forest owner has all the necessary information in order to choose a buyer on a virtual platform. However, until the existing systems of measurement have their drawbacks and, moreover, are incompatible to each other, there is an evident need in a forest engineer in preharvesting situations.

Commercial harvesting in this study may be considered as a basis sufficient enough for validating the estimations results, produced by different methods of measurements. It challenged the contents of the information provided by the methods, e.g., showed that the methods lack data to assist a forest owner in calculating incomes. Neither of the method had a tool to predict the volumes of defected timber. FMP and ALS data neglected the detailed assessment of the deciduous trees. It was also impossible to derive log-and-pulp breakdown directly from ALS data. In general, in order to better predict the income, the methods need to better calculate specifically the volumes of merchantable wood.

However, the commercial harvesting report does not provide the information to enable the validation of diameters distribution, as the results are delivered in measured bucking sizes. This study supports the position of Korhonen et al. (2008), who marked that "a simple means of estimating the effects of varying saw log dimensions and stand-level features, such as retention trees and disease infections, should be developed to increase the accuracy of ALS-based estimation". It is well-grounded to be applied to all the methods of the forest inventories.

The study can also contradict to one of the conclusions made by Siipilehto et al. (2016) about the costs of using ALS, Trestima and EMO solutions. They stated that "if up-to-date ABA information is available, only limited benefits can be obtained from stand-specific inventory using Trestima or EMO in mature pine or spruce-dominated forests". Though theoretically ABA data cost less than Trestima, another study is needed to calculate the costs with the view to make the ALS information applicable to the stand-level inventories, especially with the possibility to deliver information suitable for preharvesting commercial decisions.

Data collected for the purpose of the study allow further research on its basis. E.g., models for factual recovery predictions may be tested with commercial harvesting results as reference data. Another possible study may concern the timber assortments estimates and their correlation with the actually harvested volumes per assortments. What is economically better for the forest owner, to present lower or higher expectations to the market?

The operational planning still requires additional measurements for checking that the forest management decisions based on the ALS inventory are correct and for collecting information on variables that are not directly evaluated in an ALS inventory, as these variables may affect resource allocation by the wood procurement company and the pricing of the timber. One of the possible ways of development in this direction or further studies could be, for example, combining Trestima and ALS at forest inventories.

Acknowledgements

I express my gratitude to everyone who supported and guided me throughout the course of my research.

I would like to thank lecturers of NOVIA's Forestry Department Britt-Mari Fagerström, Johnny Sved and Kaj Hällfors for their kind support and patience as well as for the deep and invaluable knowledge they provided me with during my study of the forestry subjects.

I am grateful to my supervisor Johnny Sved for his help, flexible thinking and valuable answers to my many versatile questions and reflections, which facilitated the wider scope of research tasks and my more free scientific approach.

Many thanks to Kaj Hällfors for his advice and information provided for the purpose of my research. I am truly thankful for his scientific scepticism and challenging tasks he set to me.

My warm thanks I express to Head of Sustainable Coastal Management Program Anna Granberg, who always provided me with friendly advice and encouragement during my work at this study.

I would like to express my special gratitude to George Rybakov, CEO of RusFor Consult Oy Ab, whose enthusiasm, practical help and support helped to make my study true.

References

Bitterlich, W. (1984). The Relascope Idea. Relative Measurements in Forestry. *Commonwealth Agricultural Bureaux, London, UK*. p. 242.

Bollandsås, O. M., Maltamo, M., Gobakken, T. & Næsset, E. (2013). Comparing parametric and non-parametric modelling of diameter distributions on independent data using airborne laser scanning in a boreal conifer forest. *Forestry (2013) 86 (4),* 493-501.

Cajander, A. (1949). Forest types and their significance. Suomalaisen Kirjallisuuden Seuran Kirjapainon Oy, Helsinki.

Haara, A. & Korhonen, K.T. (2004). Kuvioittaisen arvioinnin luotettavuus. *Metsätieteen aikakauskirja 4/2004,* 489–508.

Holmgren, J., Barth, A., Larsson, H. & Olsson, H. (2012). Prediction of stem attributes by combining airborne laser scanning and measurements from harvesters. *Silva Fennica 46(2),* 227–239.

Holopainen, M., Vastaranta, M., Rasinmäki, J., Kalliovirta, J., Mäkinen, A., Haapanen, R., Melkas, T., Yu, X., Hyyppä, J. (2010). Uncertainty in timber assortment estimates predicted from forest inventory data. *European Journal of Forest Research 129,* 1131–1142.

Jord- och skogsbruksministeriet förordning Nr 12/13. Datum 17.6.2013, Dnr 1323/13/2013.

Järnstedt, J., Pekkarinen, A., Tuominen, S., Ginzler, C., Holopainen, M. & Viitala, R. (2012). Forest variable estimation using a high-resolution digital surface model. *ISPRS Journal of Photogrammetry and Remote Sensing 74*, 78-84.

Kaartinen, H.; Hyyppä, J.; Yu, X.; Vastaranta, M.; Hyyppä, H.; Kukko, A.; Holopainen, M.; Heipke, C.; Hirschmugl, M.; Morsdorf, F.; Næsset, E.; Pitkänen, J.; Popescu, S.; Solberg, S.; Wolf, B.M.; Wu, J.-C. (2012). An International Comparison of Individual Tree Detection and Extraction Using Airborne Laser Scanning. *Remote Sens. 2012, 4*, 950-974.

Kilkki, P. (1989). Metsänmittausoppi. Silva Carelica 3.

Korhonen, L., Peuhkurinen,, J., Malinen J., Suvanto, A., Maltamo, M., Packalen, P. and Kangas, J. (2008). The use of airborne laser scanning to estimate sawlog volumes. *Forestry* (2008) 81 (4): 499-510. doi: https://doi.org/10.1093/forestry/cpn018

Laasasenaho, J. (1982). Taper curve and volume functions for pine, spruce and birch. *Comm. Inst. For. Fenn. 108*, 1-74.

Leitner, T., Stampfer, K., Visser, R. (2014). Analysing log length measurement accuracy of harvester and processor heads. *Austrian Journal of Forest Science 131(3),* 129-146.

Lehmonen, H. (2015). Virkeshandel. In: Rantala S. (ed.). *Skogsbrukets handbok.* Borgå: Tryckeri Bookwell Oy. ISBN 978-952-6612-27-0, 229-244.

LUKE Natural Resources Institute Finland (2016). Volumes and prices in industrial roundwood trade, as per 30.12.2016. http://stat.luke.fi/en/volumes-and-prices-roundwood-trade (retrieved: 30.12.2016).

Maltamo, M., Naesset, E. & Vauhkonen, J. (eds.). (2014). Forestry Applications of Airborne Laser Scanning: Concepts and Case Studies. *Managing Forest Ecosystems Vol. 27*. Springer Science, Business Media Dordrecht, 1-3.

Mehtätalo, L. (2002). Valtakunnalliset puukohtaiset tukkivähennysmallit männylle, kuuselle, koivulle ja haavalle. *Metsätieteen aikakauskirja 4/2002*, 575–591.

Metsä Group's owner-members can update their growing stock information by taking photos with their mobile phones. http://www.metsagroup.com/en/media/Pages/Case-Updating-growing-stock-information-by-taking-photos-with-mobile-phones.aspx (retrieved: 14.10.2016).

Mäki-Hakola, M., Rintala, P. (2015). Virkeshandel. In: Rantala S. (ed.). *Skogsbrukets handbok.* Borgå: Tryckeri Bookwell Oy. ISBN 978-952-6612-27-0, 195-203.

Nasset, E. (1997b). Estimating timber volume of forest stands using airborne laser scanner data. *Remote Sensing of Environment 61 (2)*, 246–253.

Peuhkurinen, J., Maltamo, M., Malinen, J., Pitkänen, J., Packalén, P. (2007). Preharvest measurement of marked stands using airborne laser scanning. *Forest Science, Vol. 53*, Number 6, December 2007. Society of American Foresters, 653-661.

Peuhkurinen, J., Maltamo, M., Malinen, J. (2008). Estimating species-specific diameter distributions and saw log recoveries of boreal forests from airborne laser scanning data and aerial photographs: a distribution-based approach. *Silva Fennica 42(4),* 625–641.

Peuhkurinen, J. (2011). Estimating tree size distributions and timber assortment recoveries for wood procurement planning using airborne laser scanning. *Dissertationes Forestales 126.*

Piira, T., Kilpeläinen, H., Malinen, J., Wall, T. and Verkasalo, E. (2007). Leimikon puutavaralajikertymän ja myyntiarvon vaihtelu erilaisilla katkontaohjeilla. *Metsätieteen aikakauskirja 2007 (1),* 19–37.

Ponsse Oyj, Products. http://www.ponsse.com/products (retrieved: 05.01.2017).

Poso, S. (1983). Kuvioittaisen arvioimismenetelmän perusteita. Summary: Basic features of forest inventory by compartments. *Silva Fennica 17(4),* 313-349.

Rouvinen, T. (2014a). Kuvia metsästä. Metsätieteen aikakauskirja 2/2014, 119–122. http://www.metla.fi/aikakauskirja/full/ff14/ff142119.pdf (retrieved: 15.01.2015).

Rouvinen, T. (2014b). Trestima – Digital Photographs for Forest Inventory. *Sibirskij Lesnoj Zurnal (Siberian Journal of Forest Science). 2014. N. 5,* 69–76.

RusFor Consult Oy Ab, (2016). Interview with Georgy Rybakov (CEO for RusFor) on Trestima's application experiences in Russia, 19 Dec 2016.

Rybakov, G. (2015). *Mean forest volume estimation by high-resolution aerial RGB imagery and digital surface model with Trestima as validation technique.* Thesis for Bachelor of Natural Resources Degree Programme in Integrated Coastal Zone Management. University of Applied Sciences, Finland, Raseborg.

Siipilehto, J., Lindeman, H., Vastaranta, M., Yu, X., Uusitalo, J. (2016). Reliability of the predicted stand structure for clear-cut stands using optional methods: airborne laser scanning-based methods, smartphone-based forest inventory application Trestima and pre-harvest measurement tool EMO. *Silva Fennica vol. 50 no. 3 article id 1568*. http://dx.doi.org/10.14214/sf.1568.

Skogsbrukets utvecklingscentral Tapio (1996). *Skogsbrukets handbok.* Porvoo: Tryckeri Uusimaa oy. ISBN 952-9891-23-7, p. 236.

Skogscentralen (2017). MinSkog service web-portal, www.minskog.fi (retrieved: 10.02.2017).

Strandgard, M. and Walsh, D. (2012). Technical Report 225. Assessing measurement accuracy of harvester heads in Australian pine plantation. https://www.researchgate.net/publication/256761979_Assessing_measurement_accuracy_of_harvester_heads_in_Australian_pine_plantations (retrieved: 15.10.2016).

Suomen metsäkeskuksen metsävaratiedon laatuseloste, *Metsäkeskus*, (2016). http://www.metsakeskus.fi/sites/default/files/metsavaratiedonlaatuseloste.pdf (retrieved: 19.12.2016).

Suvanto, A., Maltamo, M., Packalen, P. and Kangas, J. (2005). Kuviokohtaisten puustotunnusten ennustaminen laserkeilauksella. *Metsatieteen aikakauskirja 4*, 413– 428.

Tuominen, S. (2007). Estimation of local forest attributes, utilizing two-phase sampling and auxiliary data. *University of Helsinki, Department of Forest Resource Management*.

Tuominen, S., Balazs, A., Saari, H., Pölönen, I., Sarkeala, J.& Viitala, R. (2015). Unmanned aerial system imagery and photogrammetric canopy height data in area-based estimation of forest variables. *Silva Fennica vol. 49 no. 5 article id 1348*. http://dx.doi.org/10.14214/sf.1348.

Trestima Oy. Forest Inventory System User manual v.1.2 https://trestima.s3.amazonaws.com/doccybag/TRESTIMA%20manual_Android_bb_english_1_2.pdf?Signature=pvCMuNAkHQINGuV3JcOMm0PFKA8%3D&Expires=1479427200&AWSAccessKeyId=AKIAJBQWVSQ3T5MFVBNQ (retrieved: 15.10.2016).

Trestima Oy, https://www.trestima.com/products_en/#trestima (retrieved: 15.10.2016).

Uusitalo, J. (1995). Pre-harvest measurement of pine stands for sawing production planning. *University of Helsinki, Department of Forest Resource Management, Publications 9*, p. 96.

Uusitalo, J. (1997). Measurement of pine stands for sawing production planning. *Acta Forrestalia Fennica*, p. 259.

Uusitalo, J., Kivinen, V.-P. (2000). EMO: a pre-harvest measurement tool for predicting forest composition. In: Wood properties for industrial use. Measuring of wood properties, grades and qualities in the conversion chains and global wood chain optimisation. *Proceedings of 3rd Workshop on COST Action E10, Espoo, Finland, June 19–20*, 173–180.

Varjo, J. (1995). Latvanhukkaosan pituusmallit männylle, kuuselle ja koivulle metsurimittausta varten (Predicting nonmerchantable top for pine, spruce and birch in the treewise volume estimation based on the measurements made during felling). *Metsäntutkimuslaitoksen tiedonantoja 558,* 21-23.

Vastaranta, M., Saarinen, N., Kankare, V., Holopainen, M., Kaartinen, H., Hyyppä, J., Hyyppä, H. (2014). Multisource single-tree inventory in the prediction of tree quality variables and logging recoveries. *Remote Sensing 6(4): 3475–3491*.

Vastaranta, M., Gonzalez Latorre, E., Luoma, V., Saarinen, N., Holopainen, M., Hyyppä, J. (2015). Evaluation of a smartphone app for forest sample plot measurements. *Forests 6(4): 1179–1194*.

Yu, X., Hyyppä, J., Karjalainen, M., Nurminen, K., Karila, K., Vastaranta, M., Kankare, V., Kaartinen, H., Holopainen, M., Honkavaara, E., Kukko, A., Jaakkola, A., Liang, X., Wang, Y., Hyyppä, H. and Katoh, M. (2015). Comparison of Laser and Stereo Optical, SAR and InSAR Point Clouds from Air- and Space-Borne Sources in the Retrieval of Forest Inventory Attributes. *Remote Sensing*. 2015, 7, 15933–15954, doi:10.3390/rs71215809.

Annex 1. The timber volume estimations and the harvesting results

The timber volume estimations, prepared on the basis of Trestima measurements, ALS measurements, FMP data and the forest engineer's (FE) data, compared to the actual results of harvesting performed on the harvesting areas 466 and 482, Falkgölen, 2016.

Tree species	Volume, m³	Trestima	ALS	FMP	FE estimates	Harv. results
Pine	**total 466**	**206,46**	**239,76**	**371,73**	**195,00**	-
	log 466	93,37	-	179,43	130,00	-
	pulp 466	113,09	-	192,30	65,00	-
	total 482	**666,40**	**643,91**	**505,26**	**500,00**	-
	log 482	391,83	-	321,72	320,00	-
	pulp 482	274,57	-	183,55	180,00	-
Pine, total	**Total**	**872,86**	**883,67**	**876,99**	**695,00**	**792,10**
	Total log	485,19	-	501,14	450,00	453,40
	Total pulp	387,67	-	375,85	245,00	338,70
Spruce	**total 466**	**182,16**	**103,93**	**49,64**	**90,00**	-
	log 466	66,97	-	8,01	50,00	-
	pulp 466	115,18	-	41,63	40,00	-
	total 482	**416,86**	**306,56**	**595,86**	**370,00**	-
	log 482	164,47	-	225,47	180,00	-
	pulp 482	252,39	-	370,38	190,00	-
Spruce, total	**Total**	**599,02**	**410,49**	**645,50**	**460,00**	**556,30**
	Total log	231,45	-	233,48	230,00	251,90
	Total pulp	367,57	-	412,02	230,00	304,40
Birch	**total 466**	**8,69**		**0,00**	**10,00**	-
	log 466	0,82	-	0,00	0,00	-
	pulp 466	7,87	-	0,00	10,00	-
	total 482	44,17		26,12	30,00	-
	log 482	8,71	-	0,00	10,00	-
	pulp 482	35,46	-	26,12	20,00	-
Birch, total	**Total**	**52,86**	**-**	**26,12**	**40,00**	**63,10**
	Total log	9,54	-	0,00	10,00	3,00
	Total pulp	43,33	-	26,12	30,00	60,10
Other decid.	**total 466**	0	-	0,00	-	1,90
	total 482	16,20	-	0,00	-	
Deciduous	**total 466**	**8,69**	**11,33**	**0,00**	**10,00**	**-**
	log 466	0,82	-	0,00	0,00	-

Tree species	Volume, m^3	Trestima	ALS	FMP	FE estimates	Harv. results
trees	pulp 466	7,87	-	0,00	10,00	-
	total 482	**59,88**	**27,20**	**26,12**	**30,00**	**-**
	log 482	10,05	-	0,00	10,00	-
	pulp 482	49,82	-	26,12	20,00	-
All deciduous, total	**Total**	**68,56**	**38,52**	**26,12**	**40,00**	**65,00**
	Total log	10,87	-	0,00	10,00	3,00
	Total pulp	57,69	-	26,12	30,00	62,00
Total volume	**Total**	**1540,44**	**1332,68**	**1548,61**	**1210,00**	**1413,40**
	Total 466	397,31	355,02	421,37	300,00	-
	Total 482	1143,14	977,66	1127,23	910,00	-
Total saw log	**Total log**	**728,64**	**-**	**734,62**	**690,00**	**708,30**
	total log 466	161,16	-	187,43	180,00	-
	total log 482	567,48	-	547,19	510,00	-
Share of log, %	**Total log**	**47,30%**	**-**	**47,44%**	**57,02%**	**50,11%**
	total log 466	40,56%	-	44,48%	60,00%	-
	total log 482	49,64%	-	48,54%	56,04%	-
	total log pine	55,59%	-	57,14%	64,75%	57,24%
	total log spruce	38,64%	-	36,17%	50,00%	45,28%
Total pulp	**Total pulp**	**812,93**	**-**	**813,98**	**505,00**	**705,10**

Annex 2. Trestima forest inventories report

Part 1. Harvesting site of forest compartment 466

Forest inventory report: @1

Measurement performed 01.02.2016
Measured area 2.03 ha
BA sample amount 19 pcs

Specie	BA m^2/ha	Stems pcs/ha	Stems pcs	DBH cm	Height m	Age y	Vol m^3/ha	Vol m^3	Log %
pine	11.7	307	626	22.1	18.2	70	108.1	219.9	47
spruce	11.8	637	1295	15.3	14.1	38	94.0	191.3	36
birch	0.7	35	72	15.6	15.4	38	4.5	9.2	9
Tot.	24.2	979	1992	18.6	16.2	53	206.7	420.4	40

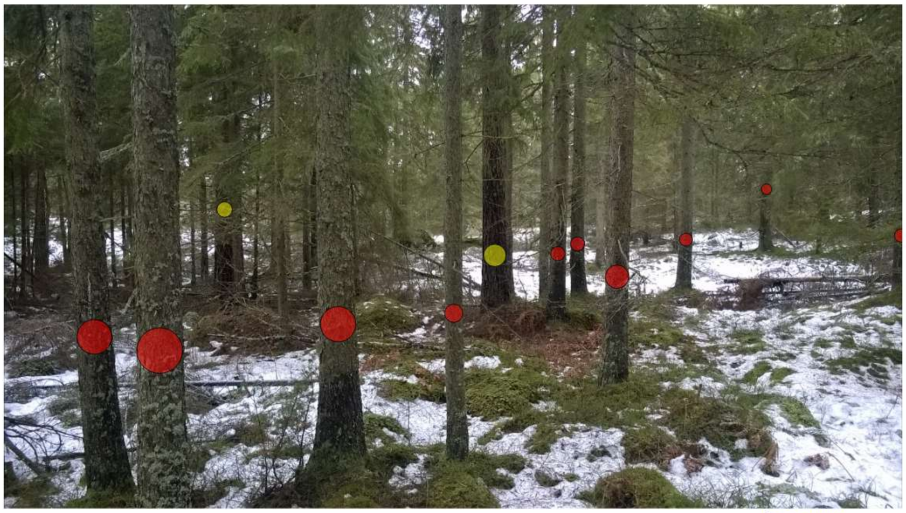
Sample size: pine: 327, spruce: 325, birch: 19, total: 671 pcs
Specie ratios: pine: 48.6 %, spruce: 48.7 %, birch: 2.8 %
BA range with 95% probability 19.0-29.4. Std. error: 12.1%


Next->
Disable
Full image
Exit
Basal area sample, 12.0 m2/ha
1/19
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 19.2 m2/ha
2/19
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 36.7 m2/ha
3/19
Report an error

Next-> Disable Full image Exit Basal area sample, 47.7 m^2/ha 4/19

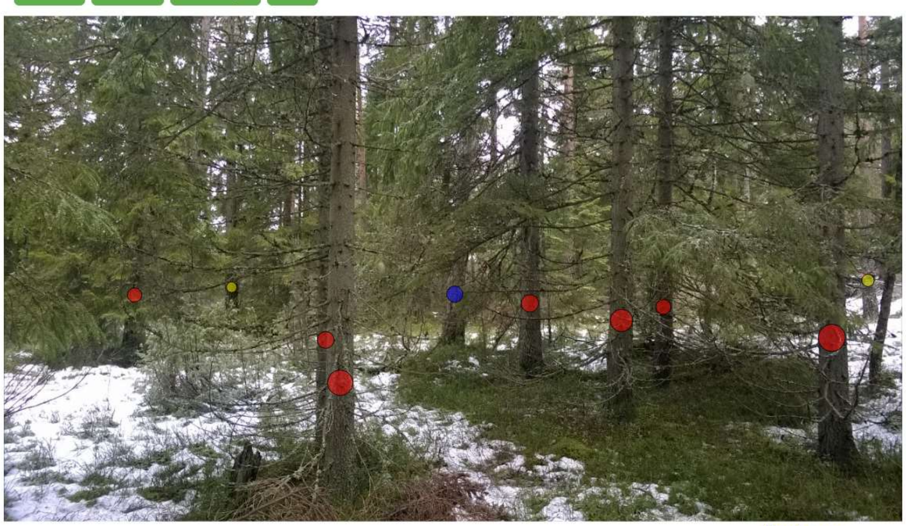


Report an error

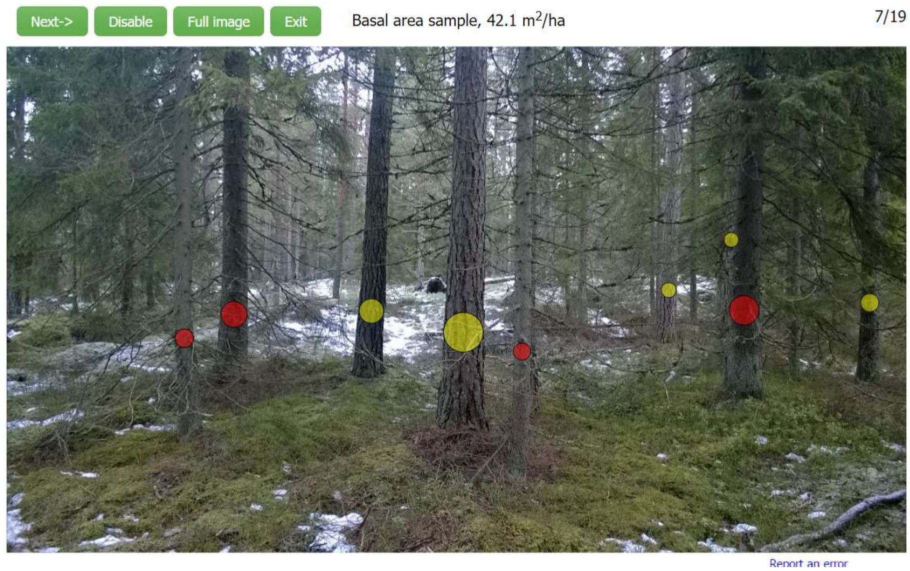
Next-> Disable Full image Exit Basal area sample, 12.3 m^2/ha 5/19

Report an error

Next-> Disable Full image Exit Basal area sample, 30.6 m^2/ha 6/19

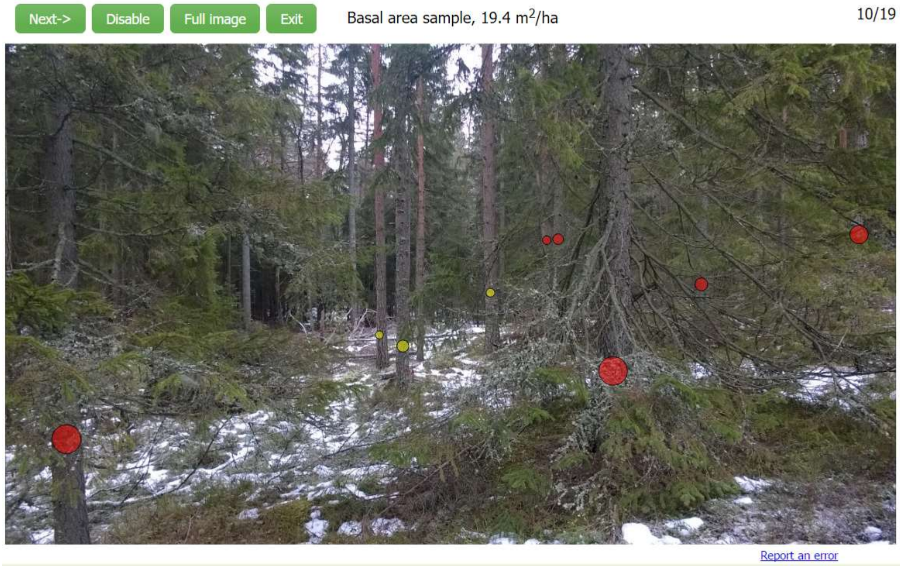


Report an error


Next->
Disable
Full image
Exit
Basal area sample, 42.1 m2/ha
7/19
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 24.2 m2/ha
8/19
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 24.8 m2/ha
9/19
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 19.4 m2/ha
10/19
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 17.0 m2/ha
11/19
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 21.0 m2/ha
12/19
Report an error

Next-> Disable Full image Exit Basal area sample, 12.0 m^2/ha 13/19

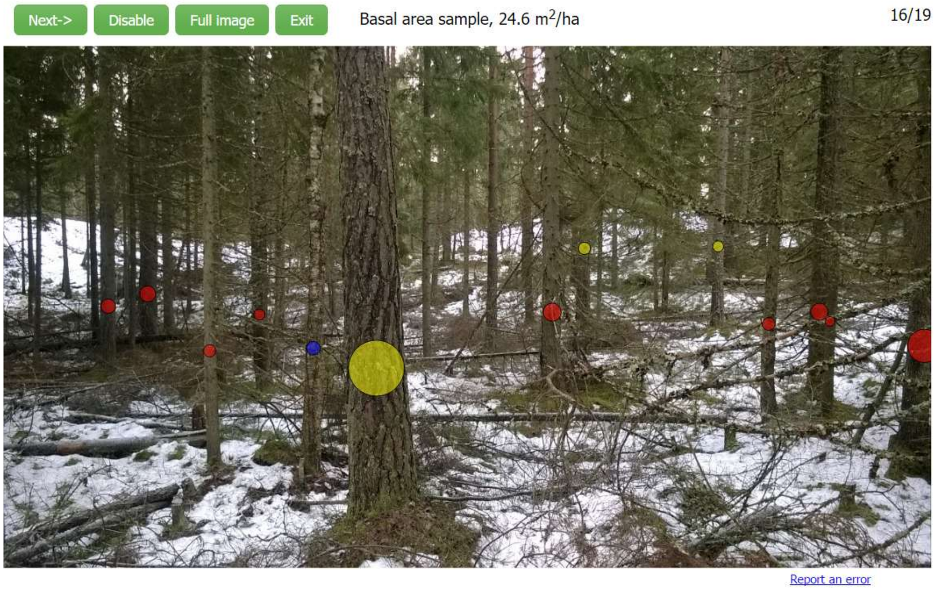
Report an error

Next-> Disable Full image Exit Basal area sample, 21.4 m^2/ha 14/19

Report an error

Next-> Disable Full image Exit Basal area sample, 9.8 m^2/ha 15/19

Report an error


Next->
Disable
Full image
Exit
Basal area sample, 24.6 m2/ha
16/19
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 36.0 m2/ha
17/19


Next->
Disable
Full image
Exit
Basal area sample, 10.0 m2/ha
18/19
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 38.8 m2/ha
19/19
Report an error

Part 2. Harvesting site of forest compartment 482

Forest inventory report: @2

Measurement performed 01.02.2016
Measured area 4.45 ha
BA sample amount 36 pcs

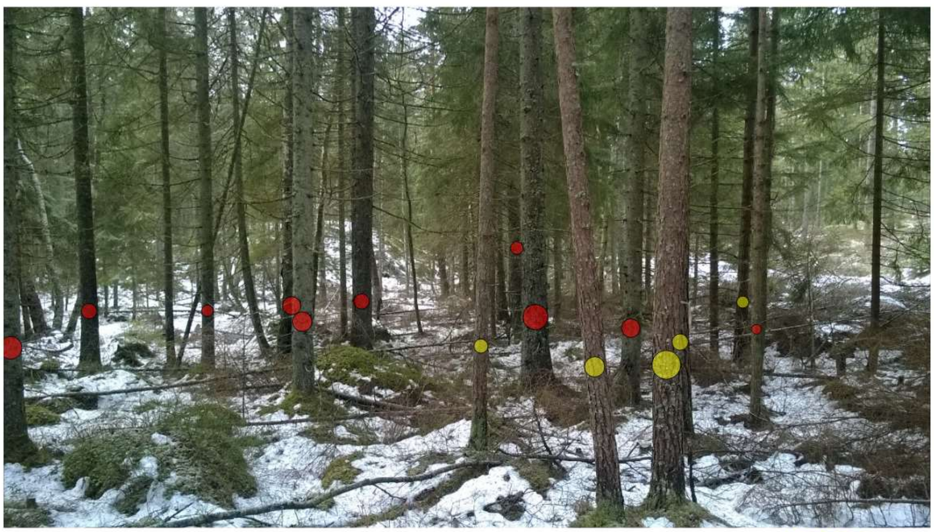
Specie	BA m^2/ha	Stems pcs/ha	Stems pcs	DBH cm	Height m	Age y	Vol m^3/ha	Vol m^3	Log %
pine	15.5	278	1240	26.7	20.9	91	156.3	696.0	59
spruce	11.7	536	2388	16.7	15.1	41	97.5	434.2	38
birch	1.6	52	230	19.6	18.1	50	11.6	51.7	24
other	0.5	23	102	17.5	16.1	43	3.9	17.6	14
Tot.	29.3	889	3960	22.1	18.4	68	269.4	1199.5	48

Sample size: pine: 814, spruce: 599, birch: 83, other: 30, total: 1525 pcs
Specie ratios: pine: 53.0 %, spruce: 39.9 %, birch: 5.3 %, other: 1.9 %
BA range with 95% probability 24.9-33.8. Std. error: 8.6%

Next-> Disable Full image Exit Basal area sample, 14.4 m²/ha 1/36

Report an error

Next-> Disable Full image Exit Basal area sample, 35.8 m²/ha 2/36



Report an error

Next-> Disable Full image Exit Basal area sample, 12.5 m²/ha 3/36

Report an error

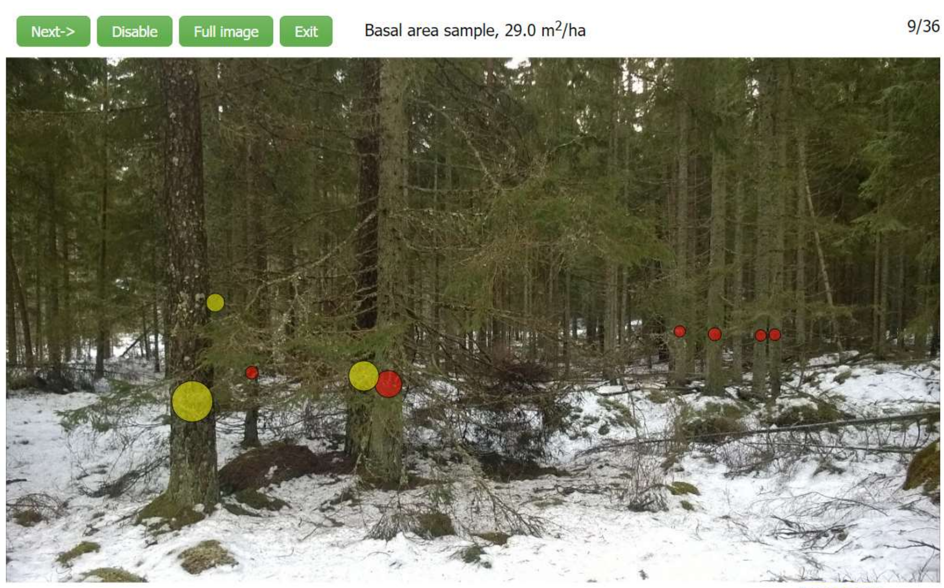

Next->
Disable
Full image
Exit
Basal area sample, 28.2 m2/ha
4/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 32.6 m2/ha
5/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 23.4 m2/ha
6/36
Report an error

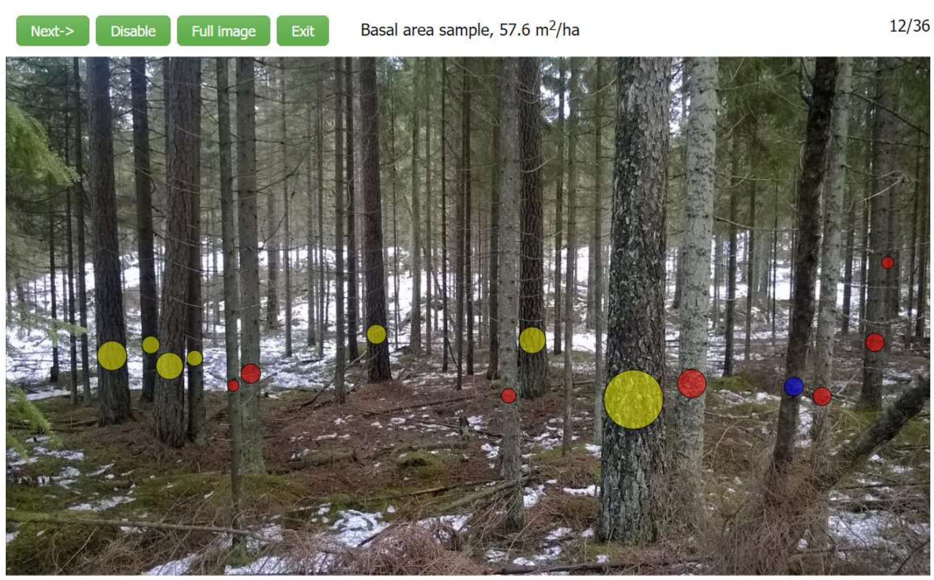

Next->
Disable
Full image
Exit
Basal area sample, 37.7 m2/ha
7/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 17.8 m2/ha
8/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 29.0 m2/ha
9/36
Report an error

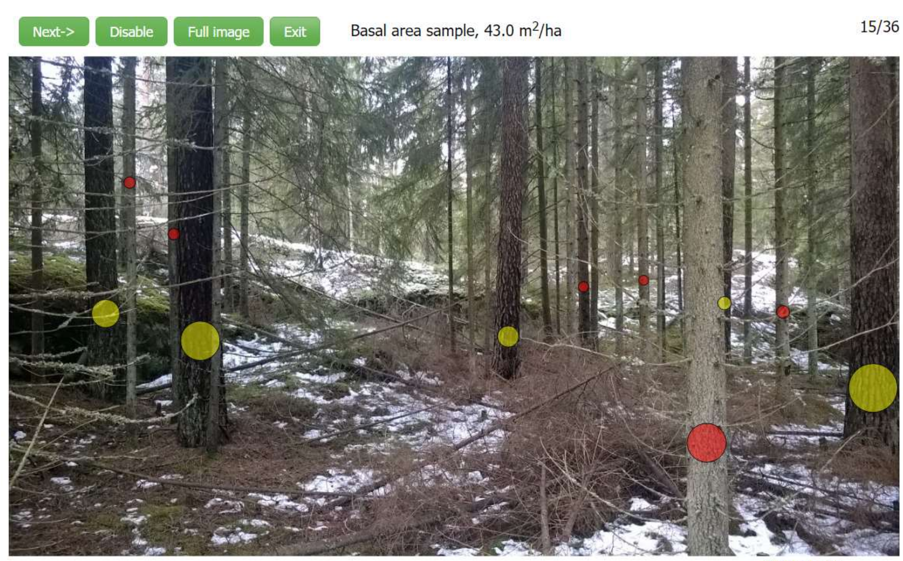

Next->
Disable
Full image
Exit
Basal area sample, 13.0 m2/ha
10/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 70.1 m2/ha
11/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 57.6 m2/ha
12/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 14.4 m2/ha
13/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 36.5 m2/ha
14/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 43.0 m2/ha
15/36
Report an error

Next-> Disable Full image Exit Basal area sample, 32.4 m^2/ha 16/36

Report an error

Next-> Disable Full image Exit Basal area sample, 18.1 m^2/ha 17/36

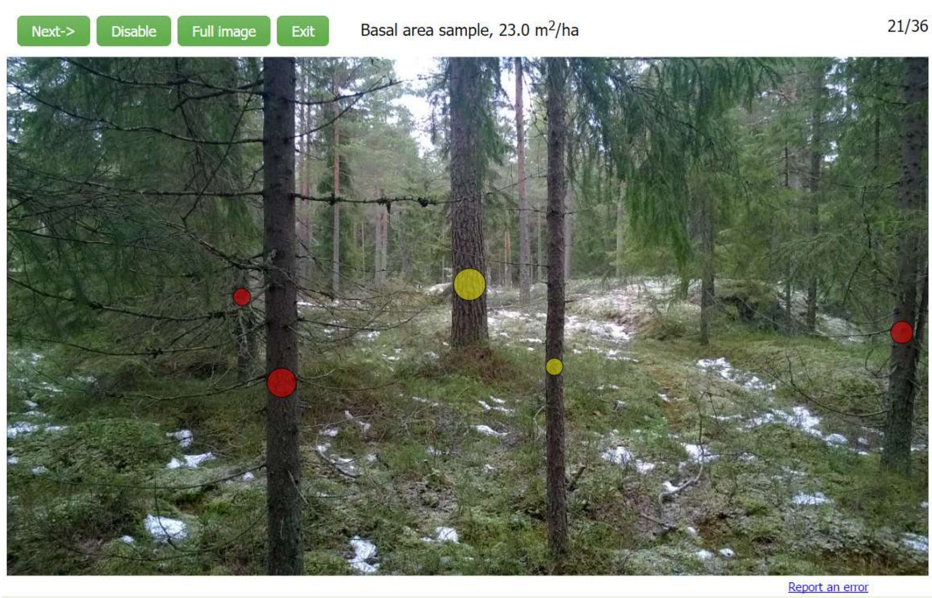
Report an error

Next-> Disable Full image Exit Basal area sample, 43.1 m^2/ha 18/36

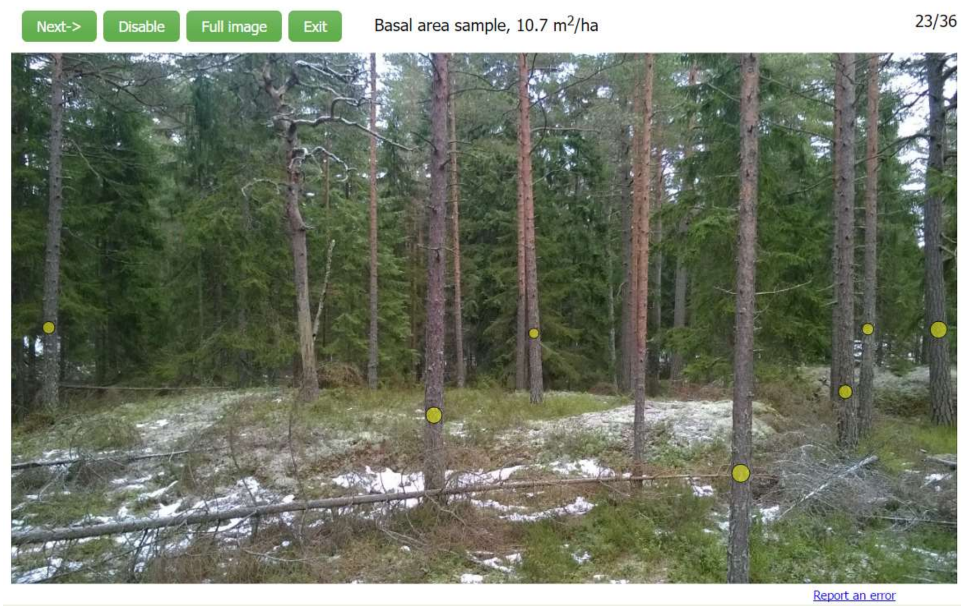
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 28.8 m2/ha
19/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 39.1 m2/ha
20/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 23.0 m2/ha
21/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 21.8 m2/ha
22/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 10.7 m2/ha
23/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 24.2 m2/ha
24/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 23.1 m²/ha
25/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 30.1 m²/ha
26/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 22.6 m²/ha
27/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 24.4 m2/ha
28/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 20.8 m2/ha
29/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 27.8 m2/ha
30/36
Report an error

Next-> Disable Full image Exit Basal area sample, 21.4 m^2/ha 31/36

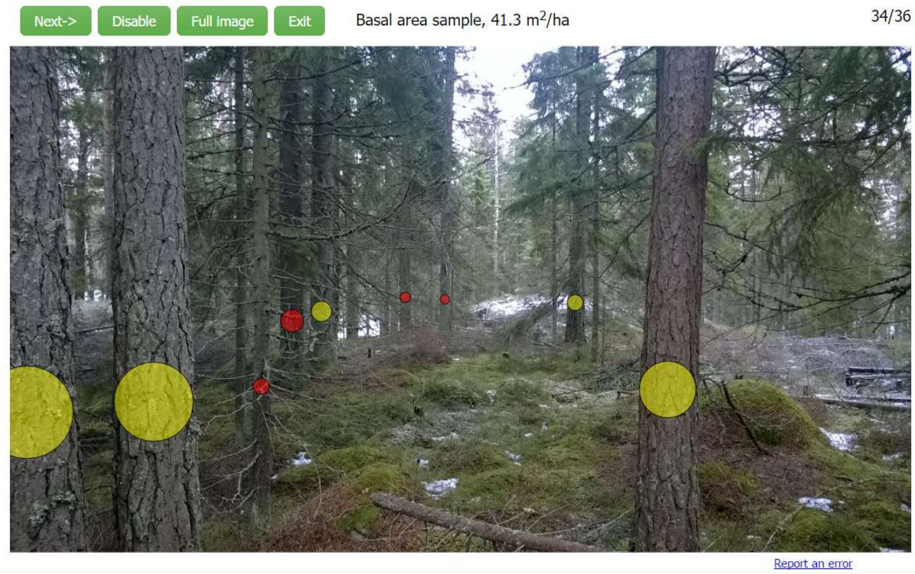
Report an error

Next-> Disable Full image Exit Basal area sample, 32.4 m^2/ha 32/36

Report an error

Next-> Disable Full image Exit Basal area sample, 9.3 m^2/ha 33/36

Report an error


Next->
Disable
Full image
Exit
Basal area sample, 41.3 m2/ha
34/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 38.8 m2/ha
35/36
Report an error


Next->
Disable
Full image
Exit
Basal area sample, 56.7 m2/ha
36/36
Report an error

Annex 3. Retention trees raw data

#	Harvesting site	Tree species	Diameter, cm	Height, m	Volume, m^3	Comments
1	466	spruce	17	11	0,12	
2	466	spruce	22	13	0,23	
3	466	pine	39	23	1,24	
4	466	spruce	34	22	0,87	
5	466	spruce	14,5	10	0,08	
6	466	spruce	19	12	0,16	
7	466	spruce	24	12	0,24	
8	466	spruce	25	17	0,38	
9	466	pine	16	14	0,14	
10	466	aspen	30	18	0,53	
11	466	pine	39	20	1,09	
12	466	pine	44	19	1,30	
13	466	pine	38	20	1,04	
14	466	spruce	24	18	0,38	
15	466	pine	45	18	1,29	
16	466	spruce	17	16	0,18	
17	466	pine	31,5	16	0,59	
18	466	spruce	10,5	7	0,03	
19	466	spruce	19	15	0,21	
20	466	pine	20	16	0,25	
21	466	pine	15	14	0,12	
22	466	pine	43,5	17	1,15	
23	466	spruce	10	8	0,03	
24	466	pine	39	19	1,04	
25	466	pine	14,5	10	0,09	windfall
26	466	pine	25	11	0,27	windfall
27	466	pine	32	17	0,64	
28	466	birch	13	9	0,06	
29	466	pine	16	12	0,12	
30	466	pine	22	17	0,31	
31	466	pine	35	15	0,68	
32	466	spruce	9	10	0,03	
33	466	spruce	23	14	0,27	
34	466	spruce	17	12	0,13	
35	466	spruce	15	12	0,11	
36	466	aspen	48	16	0,97	
37	466	alder	31	17	0,52	

#	Harvesting site	Tree species	Diameter, cm	Height, m	Volume, m^3	Comments
1	482	spruce	15	7	0,06	
2	482	pine	45	16	1,16	
3	482	pine	17	6	0,08	
4	482	pine	9	10	0,03	
5	482	pine	18,5	9	0,13	
6	482	pine	17	8	0,10	
7	482	pine	20	14	0,22	
8	482	pine	9	8	0,03	
9	482	pine	35	16	0,72	
10	482	spruce	12	10	0,06	
11	482	pine	14	7	0,06	
12	482	pine	10	8	0,03	
13	482	pine	12	10	0,06	
14	482	pine	18	12	0,16	
15	482	spruce	9	5	0,02	
16	482	pine	27	13	0,37	
17	482	spruce	20	10	0,14	
18	482	pine	27	13	0,37	
19	482	pine	29,5	14	0,46	
20	482	pine	17	11	0,13	
21	482	spruce	9	7	0,02	
22	482	spruce	8	6	0,02	
23	482	spruce	8	5	0,01	
24	482	spruce	15	11	0,10	
25	482	spruce	13	10	0,07	
26	482	spruce	13	10	0,07	
27	482	birch	45	20	1,13	
28	482	spruce	13	10	0,07	
29	482	spruce	8	7	0,02	
30	482	spruce	8	6	0,02	
31	482	spruce	14	10	0,08	
32	482	pine	21,5	17	0,30	
33	482	spruce	18	10	0,12	
34	482	pine	20,5	13	0,21	
35	482	pine	15	11	0,10	
36	482	pine	22	16	0,30	
37	482	pine	27	17	0,46	windfall
38	482	pine	16	11	0,11	
39	482	spruce	14	7	0,05	
40	482	spruce	8	6	0,02	
41	482	pine	17	7	0,09	
42	482	spruce	12	7	0,04	
43	482	spruce	12	8	0,05	
44	482	spruce	12	9	0,05	

#	Harvesting site	Tree species	Diameter, cm	Height, m	Volume, m^3	Comments
45	482	pine	48	20	1,61	
46	482	spruce	14,5	13	0,11	
47	482	spruce	16	11	0,11	
48	482	spruce	10	10	0,04	
49	482	pine	36	16	0,76	
50	482	spruce	16	12	0,12	
51	482	spruce	13	11	0,07	
52	482	spruce	13	7	0,05	
53	482	spruce	13	7	0,05	
54	482	spruce	19,5	13	0,18	
55	482	spruce	18	13	0,16	
56	482	spruce	8	7	0,02	
57	482	pine	25	18	0,42	
58	482	pine	37	20	0,98	
59	482	pine	22	14	0,26	
60	482	pine	15	10	0,09	
61	482	pine	45	20	1,42	
62	482	pine	10	9	0,04	
63	482	pine	24	17	0,37	
64	482	pine	11	9	0,05	
65	482	pine	23,5	14	0,30	
66	482	pine	18	13	0,17	
67	482	spruce	13,5	7	0,05	
68	482	birch	31	15	0,46	
69	482	pine	13,5	9	0,07	
70	482	pine	37	17	0,85	
71	482	pine	9	7	0,03	
72	482	pine	9	7	0,03	
73	482	pine	18	10	0,13	
74	482	pine	26	12	0,32	
75	482	pine	44	20	1,36	
76	482	pine	45	18	1,29	
77	482	pine	25	20	0,46	
78	482	pine	38,5	18	0,96	
79	482	spruce	12,5	7	0,04	
80	482	birch	31	15	0,46	
81	482	pine	45	20	1,42	
82	482	pine	35,5	18	0,83	
83	482	pine	26	19	0,48	
84	482	pine	18,5	15	0,20	
85	482	spruce	9	7	0,02	
86	482	spruce	9	6	0,02	
87	482	spruce	13	9	0,06	
88	482	spruce	13	9	0,06	

#	Harvesting site	Tree species	Diameter, cm	Height, m	Volume, m^3	Comments
89	482	spruce	12	9	0,05	
90	482	spruce	15	11	0,10	
91	482	aspen	48	22	1,38	
92	482	birch	38	21	0,92	
93	482	birch	27,5	21	0,54	
94	482	spruce	15,5	13	0,12	
95	482	spruce	11,5	10	0,05	
96	482	pine	33	20	0,79	
97	482	spruce	11,5	10	0,05	
98	482	spruce	11	10	0,05	
99	482	spruce	16	17	0,18	
100	482	spruce	17	17	0,20	
101	482	spruce	16	14	0,14	
102	482	birch	25	19	0,41	
103	482	spruce	13	9	0,06	
104	482	spruce	12	9	0,05	
105	482	spruce	19	18	0,26	
106	482	spruce	20	18	0,28	
107	482	birch	12	15	0,08	
108	482	spruce	8	6	0,02	
109	482	birch	34	18	0,65	
110	482	spruce	13	8	0,05	
111	482	spruce	16	10	0,10	
112	482	spruce	13	9	0,06	
113	482	pine	25	16	0,38	
114	482	spruce	15	11	0,10	
115	482	birch	18,5	12	0,15	
116	482	spruce	18	13	0,16	
117	482	spruce	15,5	10	0,09	windfall
118	482	spruce	9,5	10	0,04	windfall
119	482	spruce	13	9	0,06	windfall
120	482	birch	14	12	0,09	
121	482	spruce	13	9	0,06	
122	482	pine	32	17	0,64	
123	482	birch	23	16	0,29	
124	482	birch	20	16	0,23	
125	482	birch	13	11	0,07	
126	482	birch	14	11	0,08	
127	482	spruce	9,5	5	0,02	
128	482	spruce	9	5	0,02	
129	482	pine	18,5	17	0,22	
130	482	pine	23	15	0,30	