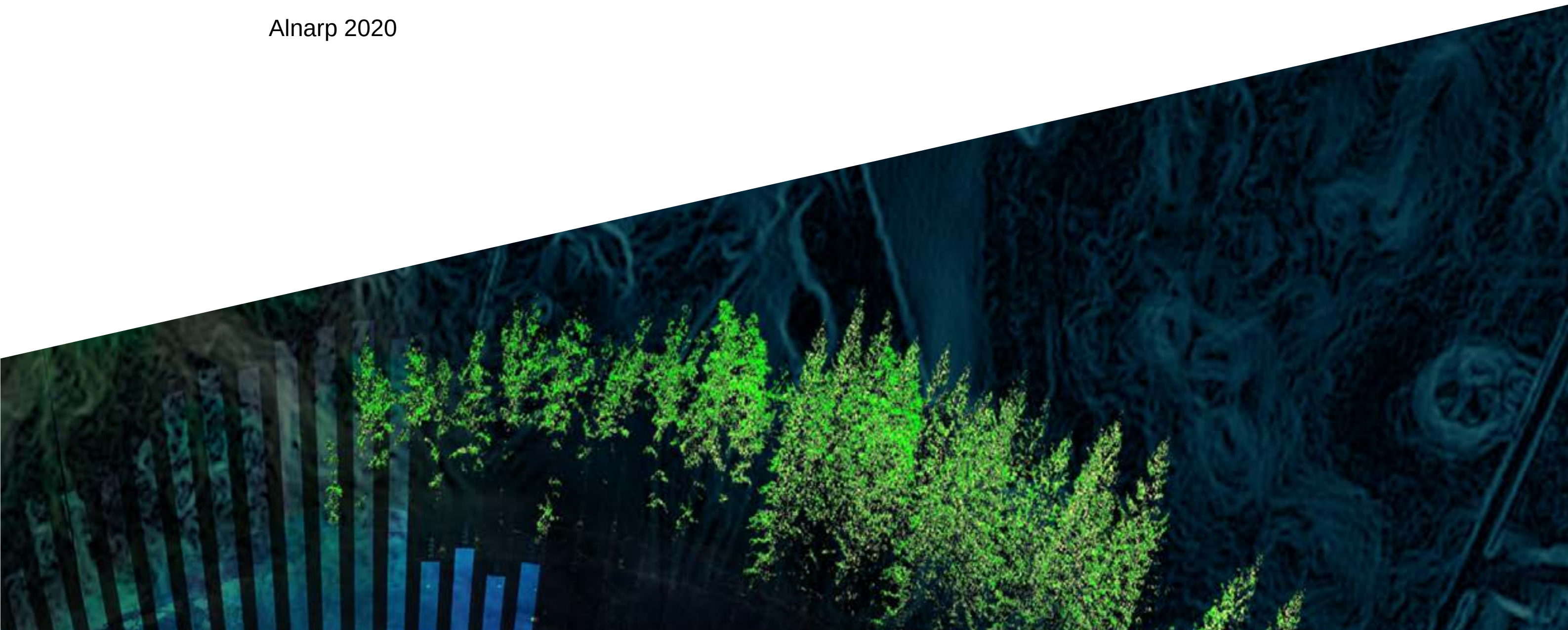
Accuracy of mobile forest inventory application Katam^{TM} Forest

– Evaluation of accuracy in different forest types and comparison to conventional inventory methods

Kristjan Täll

Master Thesis • 30 credits
EUROFORESTER
Master Thesis no. 333
Alnarp 2020



Accuracy of mobile forest inventory application Katam^{TM} Forest

Evaluation of accuracy in different forest types and comparison to conventional inventory methods

Kristjan Täll

Supervisor:	Emma Holmström, SLU, Southern Swedish Forest Research Centre
Examiner:	Eric Agestam**,** SLU, Southern Swedish Forest Research Centre

Credits:	30 credits
Level:	Advanced level A2E
Course title:	Master thesis in Forest Science
Course code:	EX0984
Programme/education:	Euroforester Master Programme SM001
Course coordinating dept:	Southern Swedish Forest Research Centre
Place of publication:	Alnarp
Year of publication:	2020

Keywords: Katam^{TM} Forest, mobile application, novel forest inventory methods, Norway spruce, habitat protection stands.

Swedish University of Agricultural Sciences
Faculty of Forest Sciences
Southern Swedish Forest Research Centre

Archiving and publishing

Approved students' theses at SLU are published electronically. As a student, you have the copyright to your own work and need to approve the electronic publishing. When you have approved, metadata and full text of your thesis will be visible and searchable online. When the document is uploaded it is archived as a digital file.

☒ YES, I hereby give permission to publish the present thesis in accordance with the SLU agreement regarding the transfer of the right to publish a work. https://www.slu.se/en/subweb/library/publish-and-analyse/register-and-publish/agreement-for-publishing/

Abstract

In recent decades with the advancement in technology, novel forest inventory techniques for quicker and cost-efficient results have been developed. A Swedish start-up company has developed an application for smart phones called Katam^{TM} Forest which can do a forest inventory by recording videos in the stand.

Even though, more forest inventory methods are accessible, conventional methods are still widely preferred because of the accuracy. This thesis aims to test the accuracy of Katam mobile application on single tree and stand level in different types of forest by comparing it to conventional inventory methods. Six Norway spruce production stands of varying ages and four heterogenous habitat protection stands were included in this thesis.

Katam provides an easy way to quickly capture a large part of the stand, thus raising the efficiency and percentage of the stand covered comparing to conventional inventory methods. The application seems to miss smaller trees and was therefore significantly overestimating the mean diameter at breast height in conservation stands. The RMSE for dbh on single tree level was 2.9 cm in production stands and 6.9 cm in habitat protection stands. No statistically significant difference was found between inventory methods when comparing basal area (m^2 ha^{-1}), volume (m^3 ha^{-1}) or density (stems ha^{-1}) in either of the two types of stands.

Novel technologies provide an easy and accessible way to conduct a forest inventory and with the further advancement in technology and research are likely to make conventional methods obsolete in the near future. Currently, more development and calibration might be needed to fully start using Katam in mixed heterogenous stands which are not necessarily meant for production.

Keywords: Katam^{TM} Forest, mobile application, novel forest inventory methods, Norway spruce, habitat protection stands.

Kokkuvõte

Kogu metsamajandamise ajaloo jooksul on metsade takseerimisel eelistatud erinevaid traditsionaalseid proovitüki meetodeid, mis oma olemuselt on aega nõudvad ja küllaltki kulukad läbi viia. Tihtilugu tuleb aja ning kulutuste säästmiseks teha otsuseid, mis vähendavad reaalselt takseeritud pindala ning see omakorda ei pruugi anda tegelikust olukorrast adekvaatset ülevaadet. Viimastel kümnenditel on tehnoloogia areng teinud suuri hüppeid ning on ilmunud uued metsainventeerimise meetodid. Kuid tihtilugu eelistatakse endiselt traditsionaalseid meetodeid, sest nende täpsus on parem.

Rootsi idufirma Katam Technologies AB on välja töötanud äpi mobiiltelefonidele (Katam™ Forest), mis metsas videosid tehes suudab takseerida metsa, tuvastades videost puutüved ja hinnates nende rinnasdiameetrit. Äpp on välja töötatud kasutamiseks majandusmetsades. Samas on Rootsi Metsaagentuur huvitatud selle kasutamisest ka vääriselupaikade takseerimisel, et saada esialgne hinnang puidutagavarale ning hüvitada erametsaomanikke puistute kaitse alla võtmisel.

Käesoleva uurimise raames testiti mobiiläpi täpsust kuues erineva vanusega kuusepuistus ja neljas kaitse alla võetud vääriselupaigas. Katam tundub alahindavat väiksemate puude rinnasdiameetrit ning tihtilugu neid ka mitte tuvastama, mis põhjustas statistiliselt usaldusväärse keskmise rinnasdiameetri ülehindamise neljas vääriselupaiga puistus. Rinnasdiameetri ruutkeskmine hälve kuusepuistutes üksikpuu tasemel oli 2.9 cm ja vääriselupaikades 6.9 cm. Võrreldes Katami tulemusi käsitsi mõõdetud tulemustega selgus, et tihtilugu on puistu tulemused rinnaspindala (m^2 ha^{-1}), tagavara (m^3 ha^{-1}) või puistu tihedus (tk ha^{-1}) väga erinevad, kuid mitte statistiliselt usaldusväärsed.

Uued takseerimise meetodid muudavad potentsiaalselt metsade takseerimise inimeste jaoks kergemaks ja paremini kättesaadavaks ning tehnoloogiat edasi arendades asendavad varsti ajakulukad traditsionaalsed meetodid. Tundub, et Katam vajab endiselt kalibreerimist ja edasist arendust, et hakata seda täies mahus kasutama ka väljapool majandusmetsasid.

Table of contents

List of tables **8**
List of figures **9**
Abbreviations **10**
1. Introduction **11**
1.1. Using Katam in conservation stands 13
1.2. Katam^{TM} Forest 15
1.3. Aim of the thesis 17
2. Materials and Methods **18**
2.1. Forest types tested 18
2.2. Katam^{TM} Forest 19
2.3. Inventory design 20
2.3.1. The caliper method 21
2.3.2. Katam^{TM} Forest stand method 21
2.3.3. Katam^{TM} Forest sample plot method 22
2.4. Sample tree measurements 23
2.5. Data management 24
2.5.1. Näslund's height curve 25
2.5.2. Volume estimation 25
2.5.3. Diameter distributions 26
2.6. Data analysis 27
3. Results **29**
3.1. Katam^{TM} Forest errors in recognising stems 30
3.2. Katam^{TM} Forest single tree estimation comparison 30
3.3. Accuracy of Katam^{TM} Forest 32
3.3.1. Mean diameter at breast height and diameter distributions 32
3.3.2. Basal area 34
3.3.3. Volume 36
3.3.4. Stem density 38
4. Discussion **41**
4.1. What to consider when working with Katam^{TM} Forest 41
4.2. Katam^{TM} Forest on single tree level 42
4.3. Accuracy of Katam^{TM} Forest 43
4.3.1. Katam sample plot method 46
4.4. Novel technologies for forest inventories 46
4.4.1. Using Katam for forest inventories 47
5. Conclusions **49**
Acknowledgements **53**
Appendix 1 – Additional tables **54**
Appendix 2 – Stand theoretical densities of diameter distributions per different inventory methods **56**

List of tables

Table 1. The stands selected for the study. Stand identity, Owner/Manager, Location (coordinates in lat, long WGS84), Dominant species (%), Stand size (hectares) and Stand age. ... 19

Table 2. Number of sample trees per stand and tree species. 24

Table 3. Stand coverage (%) for stands and inventory methods.. 29

Table 4. Mean diameter and standard deviation per stand using different inventory methods. 33

Table 5. Different parameter values for Näslund's height curves.. 54

Table 6. Estimation with Katam of dbh and volume on average in 10 cm diameter classes compared to “caliper data”, in %. 55

List of figures

Figure 1. Processed recording from Katam^{TM} Forest in a Norway spruce stand. 15
Figure 2. Output data from single recording from the KatamTM Forest application. 16
Figure 3. Output data for the entire stand from the Katam^{TM} Forest application. 16
Figure 4. Reference sign example from the mobile application. 20
Figure 5. Sample plot inventories with Katam – black line representing the sample plots, red lines the actual walking route in the nature and purple lines the plots made by Katam^{TM} Forest. Blue dots represent actual trees on the landscape. 22
Figure 6. An oak tree with a red ribbon from a Katam processed video. 23
Figure 7. Missing stem in a cluster of hornbeam (left). Missing a stem because of crookedness (right). 30
Figure 8. Mean dbh deviation from the reference line per 10 cm diameter classes. Reference line =1 represents the ratio of class mean of Katam estimated dbh / calipered dbh. 31
Figure 9. Mean volume deviation from the reference line per 10 cm diameter classes. Reference line =1 represents the ratio of class mean of Katam estimated volume / caliper method volume... 32
Figure 10. Diameter distribution of stand 32a. Density of the stems in 2 cm classes. Caliper method (left), Katam stand (middle) and Katam sample plots (right). 34
Figure 11. Diameter distribution of stand SK51. Density of stems in 2 cm classes. Caliper method (left) and Katam stand method (right). 34
Figure 12. Basal area comparison between calipered data and Katam data in production stands. C - caliper method; Ks - Katam stand method; Kp - Katam sample plot method. 35
Figure 13. Basal area comparison between calipered data and Katam data in conservation stands. C - caliper method; Ks - Katam stand method. 36
Figure 14. Volume comparison of different inventory methods in production stands. C - caliper method; Ks - Katam stand method; Kp - Katam sample plot method. 37
Figure 15. Volume comparison of different methods in conservation stands. C - caliper method; Ks - Katam stand method. 38
Figure 16. Density comparison of different methods in the production stands. C - caliper method; Ks - Katam stand method; Kp - Katam sample plot method. 39
Figure 17. Density comparison of different methods in conservation stands. C - caliper method; Ks - Katam stand method. 40

Abbreviations

ALS	Airborne laser scanning
CNN	Convolutional neural networks
DAP	Digital aerial photogrammetry
DBH	Diameter at breast height
RMSE	Root mean square error
SFA	Swedish Forest Agency
SLAM	Simultaneous localisation and mapping
TLS	Terrestrial laser scanning
UAS	Unmanned aerial system
WKH	Woodland key habitat

1. Introduction

To this date most of forest inventory measurements rely on the site measuring by using conventional techniques. On site measurements are usually carried out by placing a systematic grid of sample plots over the area for inventory (Liang *et al.* 2019). With the accessibility of forests and the structural complexity this approach is time consuming and the high labour cost will bring down the cost efficiency for the employer. With monetary and temporal restrictions some parameters cannot be captured and usually the sample area size needs to be cut down (Liang *et al.* 2019). Novel emerging technologies provide possibilities to cover the same measurements several times faster, thus saving time and therefore money. Significant amount of effort and capital has been invested into developing quicker and easier methods of doing a forest inventory (Dick *et al.* 2010; Liang *et al.* 2019). Much of the information is still needed to be collected out in the field, but the recent advances in technology have made it possible to map a wide range of necessary forest characteristics for management by using remote sensing (Vastaranta *et al.* 2011; Noordermeer *et al.* 2019).

There are several ways of remote sensing that provide a potential alternate to capture the structure of the stand, such as airborne laser scanning (ALS), terrestrial laser scanning (TLS), digital aerial photogrammetry (DAP) and satellite imaginary (White *et al* 2016). In recent years there has been advancement in drone technology and introduction of unmanned aerial systems (UAV) in forest inventory methods. Equipping drones with the necessary sensors for laser scanning or DAP will provide more accurate ways of forest inventory from closer range and on a finer scale (Zhang *et al.* 2016; Goodbody *et al.* 2018). So far, ALS have been proven to provide superior results comparing to other novel methods when taking the area covered and accuracy into consideration (Maltamo *et al.* 2006; White *et al* 2016;

Noordermeer *et al.* 2019). On the other hand, ALS is quite limited in identifying the tree species based from the laser point cloud (White *et al* 2016). Therefore, it is to be expected that in the future the combination of ALS and DAP would be used in forest inventories (Maltamo *et al.* 2006; White *et al* 2016)

But for a forest owner the easiest solution would be to use a device that most people own, and which is an inseparable part of people's lives these days. With this in mind, Katam™ Forest was created. It is a mobile application developed by a private company that allows the user to get a quick estimate of different necessary forest inventory values by taking a video of the stand. It is able to cover more ground faster than the conventional sample plot technique, because it is not restricted to those sample plots (Katam n.d.). Therefore, the application will potentially also capture higher variability in the stand and give a better overview of the existing forest. The application can be used with a range of smart phones accessible to people today.

Being relatively new and still in development to improve the accuracy, there haven't been that many previous studies with using Katam in forest inventories. But Katam has been proven to be reliable tool with its precision by measuring the same trees several times – the average difference was minimal and insignificant between the repeated measurements (Andersson 2019). Previous tests in Norway spruce production forest just before final harvest have shown a slight overestimation of basal area and volume estimates for Katam (Andersson 2019). On the other hand, basal area (m^2 ha^{-1}) and stem density (stems ha^{-1}) were significantly underestimated in pine and spruce production stands in Tönnersjöheden (Bergh *et al.* unpublished).

Katam™ Forest was developed to be used in Swedish conditions of spruce or pine production forests. The stands need to have already been through at least the first commercial thinning to have a suitable stem density, size of the trees and crown structure in order for the app to work properly (Katam n.d.). Conversion to spruce forests from other tree species is in rise in Sweden, mainly because of raised browsing damage to other species from an early age and not enough market demand for other substitute tree species (Knoke *et al.* 2008; Felton *et al.* 2019). Over time, this trend has deepened the lack of heterogeneous mixed stands which could lead to a negative effect on aesthetics (Felton *et al.* 2019), recreation (Eggers *et al.* 2018), ecosystem services and biodiversity on the forest landscape (Knoke *et al.* 2008; Felton *et al.* 2010; Lindbladh, Roster 2010). Several forest inhabiting species have gone extinct or have become endangered over time in Sweden (Ericsson *et al.* 2005; Timonen *et al.* 2011). Therefore, areas with old-growth and mixtures also need to be retained and protected, but sometimes forest owners are not willing to set them aside voluntarily, if there's no proper financial incentive. It would be beneficial to also be able to use Katam in those heterogeneous forests to have a quick estimate on stand values. But in mixed forests there are obviously more problems for Katam to deal with. With too many different tree species growing in the stand, the species composition will be harder to capture. Also, the heterogeneous structure makes the use of Katam more difficult and the understory might block the view of the app to capture larger trees behind regeneration.

1.1. Using Katam in conservation stands

In Sweden production forest is mostly managed as Norway spruce (*Picea abies*) or Scots pine (*Pinus sylvestris*) homogenous monocultures (Felton *et al.* 2019). In southern Sweden, which is located in the temperate vegetation zone, conifer monocultures are far from natural forests. Here the less managed forests often have a heterogenous structure and consist mostly of different species of broadleaves. Species such as common beech (*Fagus sylvatica*) and oak species (*Quercus robus* and *Quercus petraea*) contribute disproportionately a lot to biodiversity with their old growth forms (Lindbladh *et al.* 2007; Lindbladh, Roster 2010). Therefore, conservation of those stands is needed to keep the old growth forms of those trees present in the forest landscape in Southern Sweden (Lindbladh, Roster 2010).

The implementation of woodland key habitats in 1990 in Sweden (Nitare and Noren 1992) has helped to direct the process of forest owners voluntarily setting asides parts of their production forest for nature conservation (Timonen *et al.* 2011; Bjärstig *et al.* 2019). Voluntary set-asides are a part of the integrated nature conservation strategy in Sweden (Grönlund *et al.* 2020), but the amount is still far from desired situation in order for Sweden to reach the needed environmental protection goals (Widmann 2016; Grönlund *et al.* 2020).

The problem with voluntary set-asides is also the lack of strict control and to an extent some of them are still being managed (Grönlund *et al.* 2020). With weak incentives of voluntary protection, a lot of forest owners were showing little to no interest (Widmann 2016). Therefore, the government has identified cooperation with private forest owners a necessary component in order to progress with conservation goals (Widmann 2016). If making the process less top-down and providing better financial incentives to forest owners, more interest from the forest owners' side is also expected (Mänttymaa *et al.* 2009; Widmann 2016).

In order to compensate the private forest owners for setting aside their forests as habitat protection areas as justly as possible, the current approach from Swedish Forest Agency (SFA) has been to caliper all the trees in the stand to get the best estimate of volume and monetary value. That is extraordinarily time and resource consuming and after getting the data, there is no guarantee that the forest owner would sign the contract based on the numbers. Which means a lot of budgeted money for nature conservation might be wasted unnecessarily. With the COVID-19 virus-induced economic crisis (Baker *et al.* 2020; Beine *et al.* 2020), the money allocated for proper set-aside compensation and nature conservation is more likely to be limited in the upcoming years (Paliogiannis *et al.* 2019). In order to save money for actual compensation of set-asides, it is necessary for the SFA to get an estimate of the stand value quickly and easily. Katam™ Forest provides an opportunity for that and could potentially make conventional inventory methods obsolete in the near future. Although, the current idea of SFA is to use Katam™ Forest in order to get the first estimate which then to present to the forest owner. Based on the estimate from the application, the forest owner would then decide whether or not to go forward with the set-aside contract. If the forest owner is still interested, then SFA would caliper the stand to compensate the forest owner as fairly as possible.

1.2. Katam^{TM} Forest

Katam^{TM} Forest is a mobile application developed by the Swedish start-up company Katam Technologies AB. The method is based on videos taken with a smartphone in the stand. After taking a video, the application processes it and provides the user with estimated values of mean diameter at breast height (dbh), stem density (stems ha^{-1}), basal area (m^2 ha^{-1}) and volume (m^3 ha^{-1}) (Figure 1; Figure 2). The length of the video must be at least 15 seconds and the upper limit depends on the processing capability of the smart phone. The longer the video, exponentially longer the processing time. For quicker processing time, shorter videos are recommended. To use the app the operator needs to walk through the representative areas of the stand by pointing the camera of the phone sideways to capture trees from several angles. The software uses SLAM (Simultaneous localization and mapping) (Thrun 2007) to create a 3D point cloud and CNN (Convolutional Neural Networks) (Wu *et al.* 2016) to detect trees (Figure 1). A simplified 3D-model is built and from this model the app can extract measured values such as dbh, stem density, tree position, etc.

Figure 1. Processed recording from Katam^{TM} Forest in a Norway spruce stand.

Different tree species must be manually changed in the application to get an output per tree species (Figure 2). Average height of the stand must also be manually inserted in order to achieve better accuracy in volume estimations (Figure 2). In Figure 2 average height 12.4 m is noted by the operator, all other values calculated by the Katam algorithm.

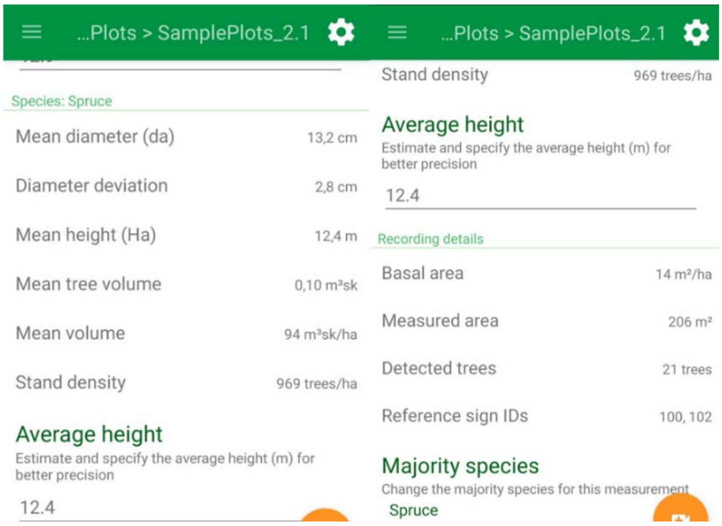


Figure 2. Output data from single recording from the KatamTM Forest application.

When taking several recordings in a stand, the application will merge estimated data together weighing them by estimated area of each recording (Figure 3).

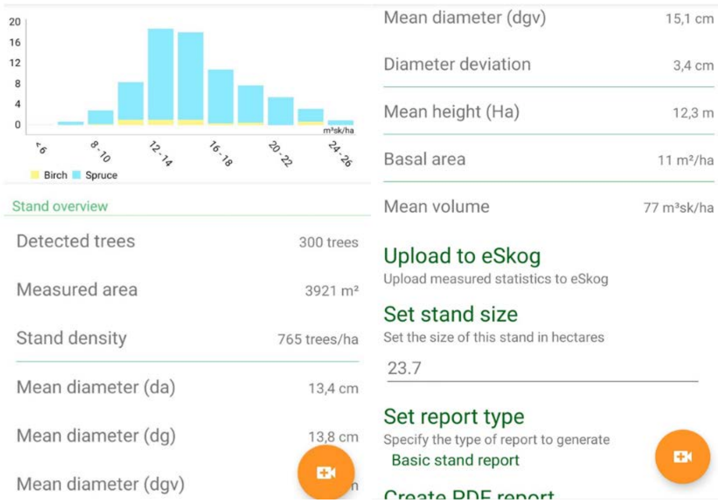


Figure 3. Output data for the entire stand from the Katam™ Forest application.

It can be chosen which recordings to include in a specific stand. There is also a possibility to export all the data per stand as a pdf report, which would be easy to print and disseminate. For the exported report, the stand area in hectares must first be manually inserted for it to calculate the necessary data for the entire stand based on the number of recordings included in the data (Figure 3).

1.3. Aim of the thesis

There is a need for more efficient and time saving methods to estimate stand characteristics, especially in the cases when the money spent on field inventories lowers the budget for the actual reason of doing those inventories (for instance nature conservation). The aim of the thesis is to find out whether new emerging technologies (e.g. in this case Katam™ Forest) are reliable and accurate enough to be used in different types of forests in Southern Sweden. In order to achieve this, the following objectives were raised:

1. For what type of trees might Katam™ Forest not work and in which situations it stops working? Based on that, would using it in non-production forest be feasible?
2. Is there a difference on single tree level when comparing diameters? And what are the implications of that to volume?
3. Does the forest type and structure change the outcome of the accuracy of stand level estimates, such as:
    a. mean diameter at breast height and diameter distributions
    b. basal area (m^2 ha^{-1})
    c. volume estimates (m^3 ha^{-1})
    d. stem density (stems ha^{-1})

Objective 1 was investigated when going through the videos after processing to check the quality of them. Objective number 2 was investigated by comparing the root mean square error (RMSE) over the range of the measured tree diameter and calculated volume. Objective number 3 was tested by the following hypothesis: there is no significant difference between calipered and Katam results when comparing stand level outputs.

Different forest types include 6 stands of spruce production forests of various ages after thinning(s) and 4 conservation stands of (mixed) broadleaves with different structure. SFA and Katam representatives would be let known of the results and conclusions.

2. Materials and Methods

2.1. Forest types tested

Forest stands from two categories of forest types were selected for the study. The standing stock was estimated primarily by measuring diameter at breast height (dbh) and stem density. Dbh is defined as diameter of a tree stem 1.3 metres from the ground.

Homogenous planted Norway spruce stands (production forest) were contrasted to heterogeneous mixed stands (conservation forest). In total 10 different stands were included in this thesis and all of them had their dbh measured with two methods: by manual measurement with a caliper and by Katam. The caliper measurements were made in either sample plots or by complete measurements of all trees within stand borders. Due to the variation in the origin of provision of stand data, earlier measurements had different sampling techniques, which had to be corrected for in the comparisons, see sections below. In addition, sample trees, within sample plots or random in the stands, were measured at the time with the Katam video recordings.

The production stands were a sample of stands provided from Sveaskog and private landowners. Both young and old stands were selected, in the stage between first commercial thinning and final felling, in the ages between 20 and 60 years (Table 1).

The heterogenous and mixed conservation stands were selected by the SFA. The stands are owned by private owners and are set-aside as nature conservation areas or habitat protection areas. Suitable stands were selected among the list with following criteria: 1) beech and oak dominated stands; 2) the calipered data must be from the 2019 vegetation period. Thus, 4 different conservation stands were chosen to be included (Table 1).

Table 1. The stands selected for the study. Stand identity, Owner/Manager, Location (coordinates in lat, long WGS84), Dominant species (%), Stand size (hectares) and Stand age.

Stand	Owner/ manager	Coordinates		Dominant species	Stand area	Stand age
		N	E		*ha*	Years
53	Sveaskog	57.41918	12.48266	Spruce 100	10	23
54	Sveaskog	57.41772	12.48719	Spruce 100	6.6	26
2032	Södra	56.00431	13.83134	Spruce 90, Broadleaf 10	3	47
2033	Södra	56.004295	13.8293	Spruce 100	3.3	40
32a	Björnstorp	55.62611	13.44876	Spruce 100	4.22	53
38b	Björnstorp	55.62368	13.43353	Spruce 100	3.55	57
SK40	SFA	56.19927	13.33677	Oak 40, Beech 30, Hornbeam 20, Lime 10	1.7	100
SK51	SFA	56.08911	13.12486	Beech 100	17.7	130
SK69	SFA	56.34305	14.11398	Beech 60, Spruce 20	1.5	100
SK501	SFA	55.89344	13.61693	Oak 40, Beech 50	1.2	100

2.2. Katam™ Forest

When recording the videos on the actual forest terrain all guidelines from Katam (n.d.) tried to be followed as best as possible while still trying to have the necessary measurables in the video for future data analysis. Keeping videos short for shorter processing time was only necessary in the beginning in couple of production stands to learn the capabilities of the application on the spot. Therefore, the length of the videos later on, when processing on the spot was not necessary anymore, was usually aimed to be between 60-80 seconds. A suitable walking pace was selected based on the stand characteristics. Fastest pace could be used in older production stands, slower for younger production stands where there were plenty of residuals on the ground from previous thinning. Usually conservation stands demanded slower walking pace comparing to production stands due to lying deadwood, being located on a slope or the need to manoeuvre around smaller trees.

Sometimes it can happen, due to video quality or stand structure, that Katam doesn't add some trees automatically, because it is not entirely sure about the location of the tree in the 3D grid or something else went wrong with processing the tree. Those trees are mostly still existing in the background and could be added manually later by clicking on the tree when watching through the processed videos. When possible, this was done for the recordings included in this thesis. When adding those trees manually it could also be roughly estimated how many trees Katam missed entirely.

For this master's thesis reference signs from Katam were used (Figure 4). Using reference signs should help to adjust the measurements by the algorithm for more accurate results. They need to be placed 10-20 metres from the start and end point of the video recording and need to be 20-30 metres away from each other.

Figure 4. Reference sign example from the mobile application.

2.3. Inventory design

The inventory design for evaluation of different forest types was made with stand level data. In the production stands three measuring methods were compared: 1) caliper method; 2) Katam stand method; 3) Katam sample plot method. In conservation stands only the first two methods were used.

2.3.1. The caliper method

The caliper method was used as a reference data for results from other inventory methods. Data for the caliper method was collected from different sources and therefore the sampling design differed slightly. For all stands, the inventory was therefore coupled with measurements of sample trees, which was consistent for all stands in this study (see below in section 2.4). Trees with over 8 cm in dbh were calipered. Multi stem trees were counted as multi stem when the split was below 1.3 m and then all stems were calipered as single trees.

In stands 53 and 54, the calipered data was retrieved from a previous study (Magnus Persson Linnaeus University, unpublished data). Ten sample plots had been measured in a systematic grid in both stands. The plots had a radius of 10 metres, making the total area of each sample plot 314 m^2. In stands 2032, 2033, 32a and 38b, three rectangle sample plots of 10x40 metres (area 400 m^2) were established within this study. No sample plots were established in stands SK40, SK51, SK69, SK501, because in these 4 stands (Table 1) a complete inventory had been made by SFA where all stems with dbh> 8 cm were registered with dbh and species.

2.3.2. Katam™ Forest stand method

The application Katam™ Forest was tested by using two different inventory designs. Stand method, which is how the application is designed to be used, was to take recordings by simply walking through the forest. The number of recordings was adjusted to stand size, topography and stem density, so that all reasonably accessible parts of the stands had been recorded.

2.3.3. Katam™ Forest sample plot method

The established sample plots in production stands also provided the opportunity to compare Katam™ Forest results by only taking recordings on sample plot level. In this case, most of the trees included in the recordings are the same as calipered. In the circular sample plots located in the younger spruce production forest, the mobile application was used to make 2 recordings. The circular plot was split in half and a video was recorded by walking in elliptical circles around each half (Figure 5). In the older spruce stands, the mobile application recording was carried out by walking along the 40-metre side of the sample plot (Figure 5).

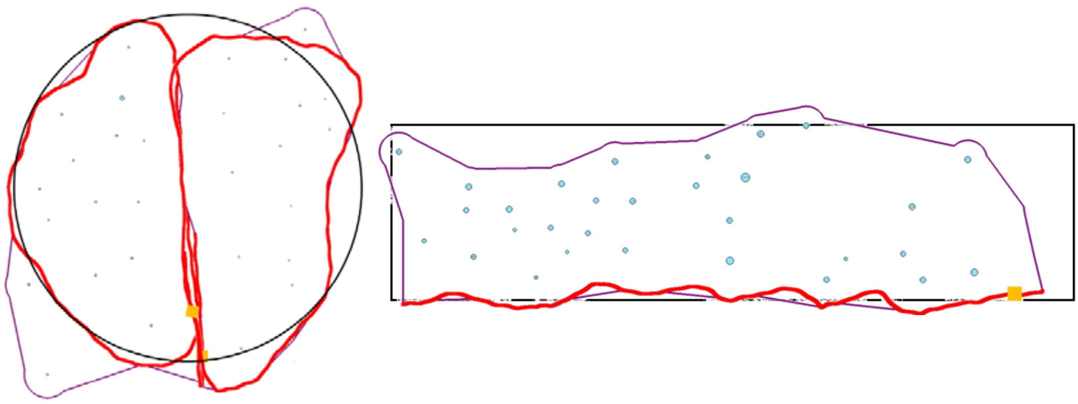


Figure 5. Sample plot inventories with Katam – black line representing the sample plots, red lines the actual walking route in the nature and purple lines the plots made by Katam™ Forest. Blue dots represent actual trees on the landscape.

Splitting the sample plot in two for Katam recordings in circular sample plots was mainly done because of following reasons:

1. when walking around the circumference line in a 10-metre radius plot the mobile application might not be able to recognize trees in the very centre of the plot, because the application reaches the limit of its penetrating depth. That is also more likely to happen with smaller diameter trees in younger stands. Similar problems are present in mobile laser scanning (Holmgen *et al.* 2019);

2. to keep the length of the recordings at a minimum which cuts down processing time drastically. With the lower processing time of the videos, they could be already processed in the forest and checked if the recording was of good quality. Which was necessary to do so in the beginning of the fieldwork to learn the capabilities of the mobile application.

Depending on the walkability of the forest, not all the trees that were included in the sample plots might end up being recorded in the videos or some extra trees might have ended up in the videos.

The heterogeneous stands had been inventoried in full and not by using sample plots. Therefore, the Katam sample plot method was not used for the conservation stands.

2.4. Sample tree measurements

In all stands, a selection of sample trees was measured. Dominant trees were selected in production stands. In conservation stands, in addition to dominant trees, intermediate and understory trees were also selected by the author of this thesis. Most of the sample trees were marked with ribbons of different colours and thereby could be recognized from the processed Katam recordings later on (Figure 6). All the trees marked and recognised by Katam had specific IDs inserted to them in the app's editor mode, so those trees could be matched to the calipered dbh data.

Figure 6. An oak tree with a red ribbon from a Katam processed video.

In the production stands this selection of sample trees was done within the sample plots. In the 4 conservation stands, a walkable route with the app was planned and alongside this route sample trees of different necessary species were marked with ribbons.

In addition to cross calipered dbh, the height of the sample trees was measured with Haglöf's Vertex IV. If the dbh of the tree was bigger than 50 cm, a diameter measuring tape was used. In stands 53 and 54 every plot had 4-5 sample trees of spruce chosen by Magnus Persson and if the plot had any silver birch (*Betula pendula)* trees then those were also chosen as sample trees. In stands 2032, 2033, 32a and 38b 5-6 spruce trees were measured per sample plot (Table 2). In stands SK40, SK51, SK69, SK501 sample trees were measured for tree species that had at least 10% of the volume of the stand (Table 2). The objective was to get at least 15 sample trees of necessary species per stand for the SFA stands in order to estimate the height and volume of the stand (Table 2). In the 10 stands a total of 336 trees were selected as sample trees, out of which 314 were marked with ribbons and could be matched to Katam estimated data.

Table 2. Number of sample trees per stand and tree species.

Tree species	Stand no.									
	53	54	2032	2033	32a	38b	SK40	SK51	SK69	SK501
Spruce	42	46	15	14	16	16	0	0	14	0
Birch	15	7	0	0	0	0	0	0	0	0
Beech	0	0	0	0	0	0	16	34	19	19
Oak	0	0	0	0	0	0	17	0	0	14
Hornbeam	0	0	0	0	0	0	18	0	0	0
Lime	0	0	0	0	0	0	14	0	0	0

2.5. Data management

R version 3.6.2 named ”Dark and Stormy Night” which was released 12th December 2019 (R Core Team 2019) and open-sourced software R-Studio version 1.1.456 (RStudio Team 2016) were used for data management and statistical analysis. Figures were made with either Microsoft Excel or R.

2.5.1. Näslund's height curve

The stand and species specific relationship of dbh and height was estimated with the measured data from the sample trees, and used to derive functions of heights for all calipered trees without measured heights. For the height estimation, Näslund's (1936) height curve (Function 1) was fitted through the data of sample trees in order to get the coefficients β_0 and β_1 (Appendix 1 Table 5).

$$height = \frac{diameter^{\alpha}}{(\beta_0+\beta_1*diameter)^{\alpha}} + 1.3 \quad (1)$$

The suitable value for parameter α depends on the tree species (Appendix 1 Table 5), β_0 and β_1 are fitted stand and species coefficients and diameter is dbh (cm). Earlier studies showed that for Norway spruce α=3 works the best (Siipilehto 2000) and α=2 was used for birch. For beech, oak, small-leaved lime (*Tilia cordata)* and hornbeam (*Carpinus betulus*) (Table 2) different α-values of 1, 2, 3, 4, 5 were tested. The best one was chosen by subtracting the measured height from estimated height and finding the mean of the residuals. The closest the mean of residuals was to zero, the better is the model. The different parameter values from table 5 in appendix 1 were used to estimate the height of rest of the calipered trees in the stands.

Once having estimated the height of all the trees that had diameters calipered, mean height of the stand per tree species was inserted into Katam™ Forest. The corrected heights were used for the volume estimates instead of the more general height estimations within the Katam™ Forest application.

2.5.2. Volume estimation

For all of the sample trees in all of the stands (Table 1; Table 2) volume was calculated. Logarithmic values of both the dbh and calculated volume were taken, and a linear model was fitted through the data points per tree species and stand. Based on this model, volume was estimated to every single tree in the 4 different conservation stands and to the trees within sample plots in the production stands. For those tree species, where no sample trees existed, volume was estimated based on the volume of all the other trees in the stands.

The volumes for lime and hornbeam trees were calculated using Brandel's (1990) volume function for birch (Function 2). The volume for spruce trees was calculated using Brandel's (1990) spruce volume function for southern Sweden (Function 3).

$$Volume = 10^{-0.89363} * Diameter^{2.23818} * (Diameter + 20)^{-1.06930} * Height^{6.02015} * (Height - 1.3)^{-4.51472} \quad (2)$$

$$Volume = 10^{-1.02039} * diameter^{2.00128} * (diameter + 20)^{-0.47473} * height^{2.87138} * (height - 1.3)^{-1.61803} \quad (3)$$

The volumes for oak (Function 4) and beech (Function 5) were calculated using the functions from Hagberg and Matern (1975). Only the stem parts of the volumes were used for oak and beech (Hagberg & Matern 1975).

$$Volume = 0.03522 * diameter^2 * height + 0.08772 * diameter * height - 0.04905 * diameter^2 \quad (4)$$

$$Volume = 0.01275 * diameter^2 * height + 0.12368 * diameter^2 * 0.0004701 * diameter^2 * height^2 + 0.00622 * diameter * height^2 \quad (5)$$

2.5.3. Diameter distributions

The measurements of dbh by Katam was evaluated on stand level by comparisons of stand arithmetic mean diameter and the diameter distributions of the stands.

The diameter distributions of the stands were visualised using an R-package ”fitdistrplus” which creates a histogram and theoretical densities graph of the diameter distributions and adds a Weibull distribution function through the histogram (Delignette-Muller & Dutang 2015). Weibull distribution function (Weibull 1951) has been found to work best for forestry data (Burkhart & Tome

2012). The parameters (also known as scale and shape) from the Weibull functions were extracted for every stand and measuring method. The value of Weibull scale parameter determines how stretched out is the distribution along the x-axis, indicating the diameter range from the smallest to biggest trees. The shape parameter determines the slope of the distribution function, indicating the structure of the stand.

In conservation stands, 2 histograms per stand were created based on the different type of data (Appendix 2) and in the production stands 3 histograms were created per stand (Appendix 2). In the histograms diameter classes of 2 cm were used.

2.6. Data analysis

The comparison between the methods for single trees was evaluated by calculating the root mean square error (RMSE) using the standard RMSE function (6).

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{(dbh_{KAT} - dbh_{CAL})^2}{N}} \qquad (6)$$

Where N is the sample size, dbh_{KAT} is Katam estimated dbh and $dbh_{CAL}$is the cross calipered dbh.

All sample trees with ribbons were stratified into 10 cm diameter classes ranging from 0 to 100 cm. Katam estimated diameter was divided with calipered dbh giving a reference line of 1 if the diameter class mean was the same for both methods. Mean percentage deviation per diameter class was thereafter calculated.

To identify a systematic difference in the measuring method of stand characteristics, a two-factor Anova was applied to determine the significance of difference (determined by $\alpha<0.05$) between calipered values and Katam estimated values. The two factors used were the inventory method and stand identity, used as a blocking factor. Production and conservation stands were tested separately. The results were analysed per response variables of mean dbh (cm), Weibull distribution function parameters, basal area (m^2 ha^{-1}), volume per hectare (m^3 ha^{-1}) and stem density (stems ha^{-1}) and. The production stands were further analysed, adding a third inventory method, Katam sample plot method.

When significant differences between calipered data and Katam data were shown by Anova in the production stands, then Tukey's HSD (Honestly Significant Difference) test was also used to see if there is a difference with using Katam sample plots method as well.

3. Results

The percentage of stand area covered by calipered sample plots in production stands ranged from 3 to 5%. Using Katam sample plot method gave coverage percentages from 3 to 6%. The percentage of stand area covered with Katam stand method in the spruce productions stands ranged from 5 to 15% (Table 3). The percentage of stand area covered by Katam stand method in conservation stands ranged from 4 to 25% (Table 3).

The penetration depth in theory with Katam should be up to 10 meters (Katam n.d.). It proved to be quite close to 10 meters in older production stands. But it was much smaller in younger production stands (stands 53 and 54) where trees are smaller and therefore Katam area coverage is smaller than originally aimed for (Table 3).

Table 3. Stand coverage (%) for stands and inventory methods.

Stand no.	Calipered coverage of the stand	Katam stand area	No. Katam recordings	Katam stand coverage of the stand	Katam sample plot area	Katam sample plot coverage of the stand
	%	m^2		%	m^2	%
53	3	5513	11	6	3921	4
54	5	3152	7	5	4105	6
2032	4	4560	5	15	1288	4
2033	4	4586	5	14	1278	3
32a	3	3121	6	7	1107	3
38b	3	4695	6	13	1079	3
SK40	100.0	1972	5	12	-	-
SK51	100.0	6331	11	4	-	-
SK69	100.0	2784	4	19	-	-
SK501	100.0	2996	4	25	-	-

3.1. Katam™ Forest errors in recognising stems

Mostly the application doesn't completely miss trees. It can happen if the tree had several stems. If the tree only had 2 stems, then it usually counted those 2 together as a stem with a bigger diameter. When the tree had more than 2 stems, one or sometimes more of stems in the cluster of stems was missed by Katam (Figure 7). In singular cases it was seen that missing trees can also happen when the trees do not grow straight up but are crooked (Figure 7).

Figure 7. Missing stem in a cluster of hornbeam (left). Missing a stem because of crookedness (right).

The application was sometimes unable to recognise some smaller sample trees marked with ribbons between 8-10 cm of diameter and the crooked small-leaved lime in figure 7.

3.2. Katam™ Forest single tree estimation comparison

The cross-calipered diameter for the sample trees ranged from 8.8 to 96.4 cm and the range of Katam estimated diameters for the same trees ranged from 6.2 to 85.4 cm. The error was larger for the Katam method in conservation stands than in production stands. RMSE was 2.9 cm in Norway spruce production stands and 6.9 cm in conservation stands.

The error was also larger for beech compared to Norway spruce with RMSE for the spruce sample trees 3.1 cm and for beech 7.9 cm. In stand SK501 (RMSE 12.7 cm) was much higher comparing to other conservation stands SK40, SK51 and SK69 where the RMSE were 3.9 cm, 3 cm, 4.1 cm, respectively.

Comparing dbh from Katam to a cross-calipered dbh showed that Katam tends to underestimate for small and really large trees (Figure 8; Appendix 1 Table 6 for diameter classes values and number of trees in each class). For lower dbh classes (until 20 cm) and larger diameter classes (80-100 cm), the deviation for Katam estimated dbh from cross-calipered dbh was much bigger than for the diameter classes in between (Figure 8).

The trend was similar for the sample tree volume comparisons, but with bigger deviations from the reference line on volume level comparing to dbh comparison (Figure 9). The mean deviation was 8% for dbh and 17% for volume (Appendix 1 Table 6)

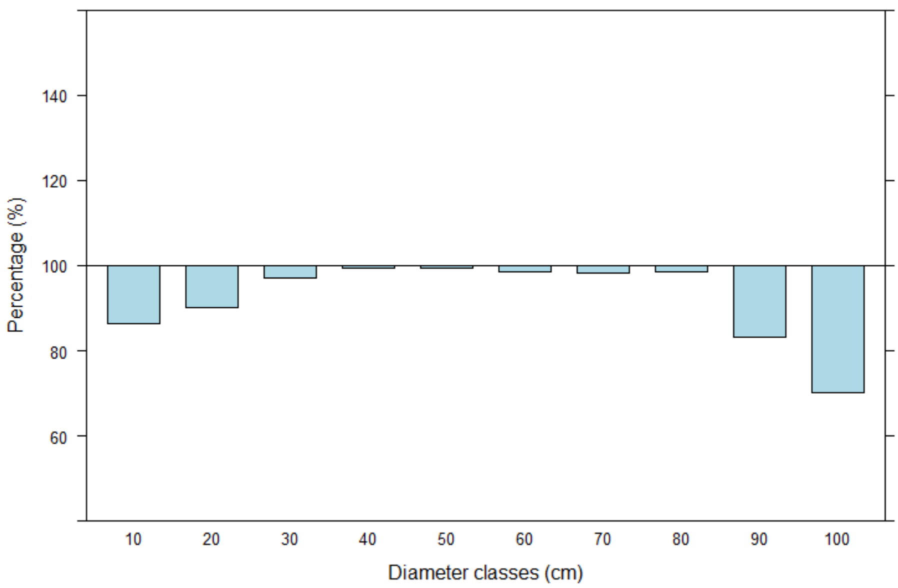


Figure 8. Mean dbh deviation from the reference line per 10 cm diameter classes. Reference line =1 represents the ratio of class mean of Katam estimated dbh / calipered dbh.

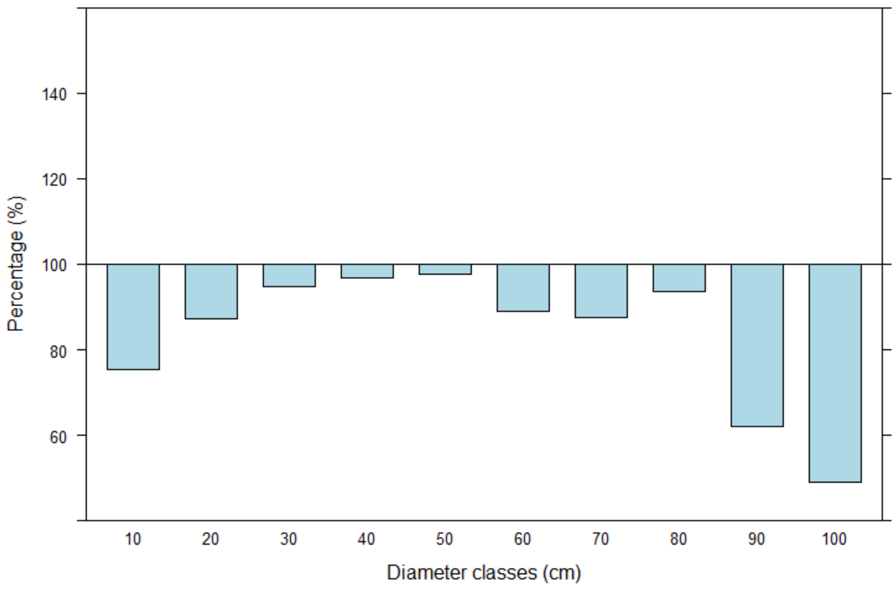


Figure 9. Mean volume deviation from the reference line per 10 cm diameter classes. Reference line =1 represents the ratio of class mean of Katam estimated volume / caliper method volume.

3.3. Accuracy of Katam™ Forest

3.3.1. Mean diameter at breast height and diameter distributions

Mean dbh in the production stands ranged from 11.4 cm in the youngest Norway spruce stands to 30.5 cm in the older stands for caliper method. For Katam stand method it ranged from 11.8 to 34.7 cm and for Katam sample plot method from 11.0 to 34.1 cm (Table 4). Mean dbh in the conservation ranged from 22.5 to 37.5 cm for caliper method and from 25.9 to 39.4 cm (Table 4).

Katam was performing differently compared to the caliper method for different forest types in mean dbh measurements. No significant difference ($p=0.691$) between the inventory methods was found in production stands. In the case of conservation stands there was a significant difference between caliper method and Katam stand method ($p=0.036$).

Table 4. Mean diameter and standard deviation per stand using different inventory methods.

	Method	Stand no.									
		53	54	2032	2033	32a	38b	SK40	SK51	SK69	SK501
DBH (cm)	Caliper	13.4	11.4	24.6	27.2	30.5	29.6	23.7	37.5	22.5	32.5
	Katam Stand	14.1	11.8	25.4	25.2	29.4	34.7	26.9	39.4	25.9	39.3
	Katam Sample Plot	13.4	11.0	24.2	25.7	31.6	34.1	-	-	-	-
SD (cm)	Caliper	3.2	2.8	6.7	7.3	6.3	6.5	14.0	19.9	12.4	26.3
	Katam Stand	4.3	2.6	7.0	6.6	7.6	7.5	14.0	16.1	11.8	23.6
	Katam Sample Plot	3.4	2.7	6.4	6.4	6.5	7.4	-	-	-	-

There was no significant difference between the inventory methods (p=0.622) when comparing scale parameter of the Weibull function in production forests.

In the production stands a significant difference was shown when comparing shape parameter of the Weibull function (p=0.019). Tukey HSD showed there to be a significant difference only between caliper method and Katam stand method (p=0.022). No significant difference was found between Katam sample plot method and the caliper method (p=0.852) or Katam stand and Katam sample plot method recordings (p=0.054).

In the conservation stands no significant difference between calipered results and Katam was found when comparing Weibull’s distribution scale parameter (p=0.052). On the other hand, there was a significant difference between the two inventory methods when comparing Weibull’s distribution shape parameter (p=0.022). For the conservation stands Katam is significantly overestimating the mean dbh and the captured amount of small diameter trees is lower (Figure 10; Appendix 2).

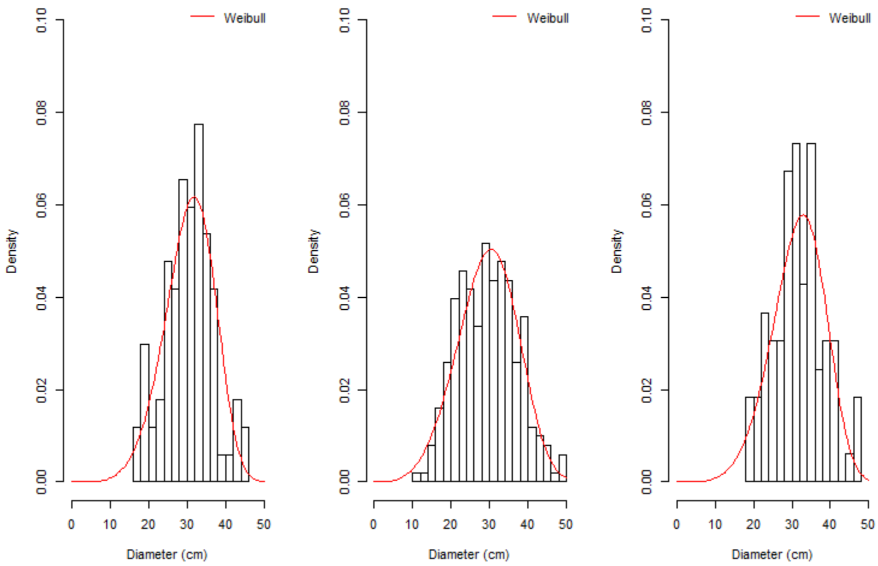


Figure 10. Diameter distribution of stand 32a. Density of the stems in 2 cm classes. Caliper method (left), Katam stand (middle) and Katam sample plots (right).

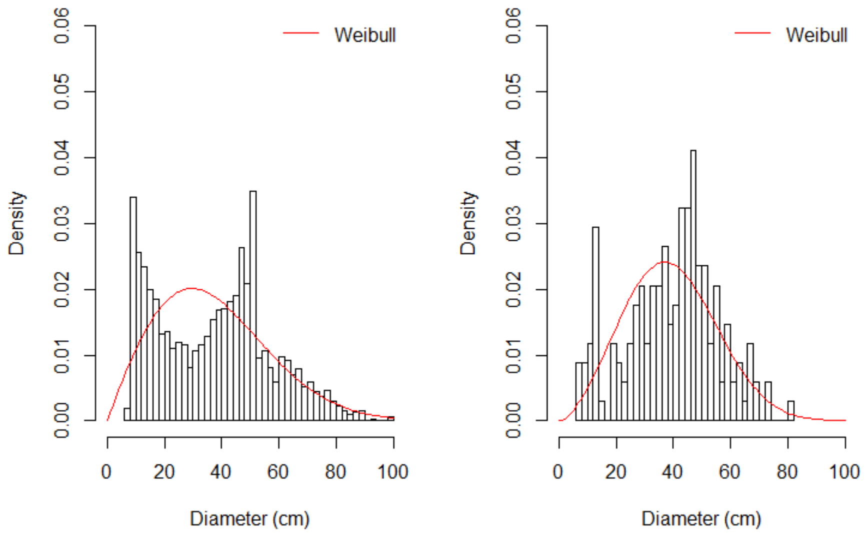


Figure 11. Diameter distribution of stand SK51. Density of stems in 2 cm classes. Caliper method (left) and Katam stand method (right).

3.3.2. Basal area

No significant difference (p=0.5003) was found between the basal area estimates in production stands. The basal area of production stands using calipered data ranged from 12 to 56 m^2 ha^{-1} and for Katam stand and Katam sample plot methods it ranged from 10 to 69 and 10 to 74 m^2 ha^{-1}, respectively (Figure 12).

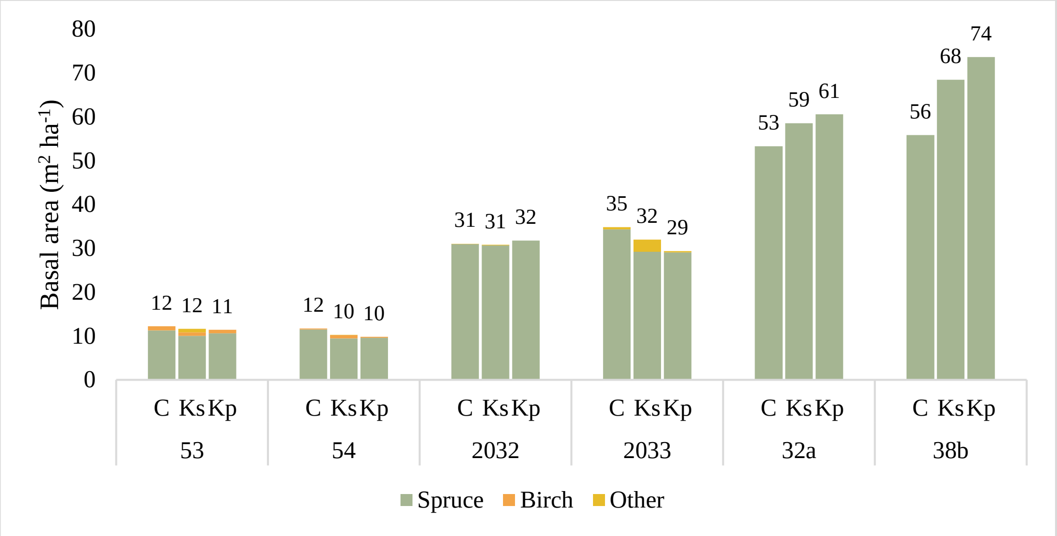


Figure 12. Basal area comparison between calipered data and Katam data in production stands. C - caliper method; Ks - Katam stand method; Kp - Katam sample plot method.

For the stand 54 Katam is underestimating the basal area with 17% for both Katam stand and sample plot methods. For the older stands (stands no. 32a and 38b) Katam is overestimating the basal area (Figure 12). The overestimation in stand 32a for Katam stand method and sample plot method are 11% and 15%, respectively. The overestimation in stand 38b for Katam stand and sample plot methods are 21% and 32%, respectively. For stands 2032 and 53 both the stand and sample plot methods gave results quite close to the calipered method (Figure 12). For stand 2033 Katam stand method underestimated the basal area by 9% and even more for the Katam sample plot method (by 17%) (Figure 12).

In conservation stands there was no significant difference in the basal area results between different inventory methods (p=0.958). The basal area ranged from 27 to 52 m^2 ha^{-1} according to calipered data and from 30 to 46 m^2 ha^{-1} according to Katam (Figure 13).

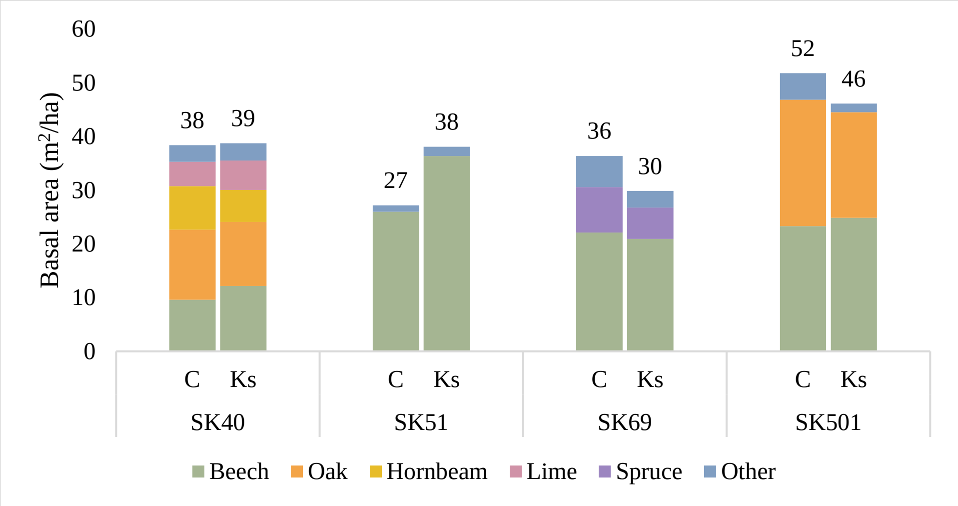


Figure 13. Basal area comparison between calipered data and Katam data in conservation stands. C - caliper method; Ks - Katam stand method.

In the conservation stands Katam was quite accurate of getting the basal area in the most diverse stand SK40 (Figure 13). It was overestimating the basal area for SK51 a lot by 41% and underestimating for SK69 and SK501, 17% and 12% respectively (Figure 13).

3.3.3. Volume

There was no significant difference between the calipered data and Katam estimates when comparing the volume per hectare values in production stands (p=0.354). The volume per hectare values ranged in the production forests from 75 to 689 m^3 ha^{-1} for the calipered data. For Katam stand and Katam sample plot methods it ranged from 60 to 808 m^3/ha and from 59 to 874 m^3 ha^{-1}, respectively (Figure 14).

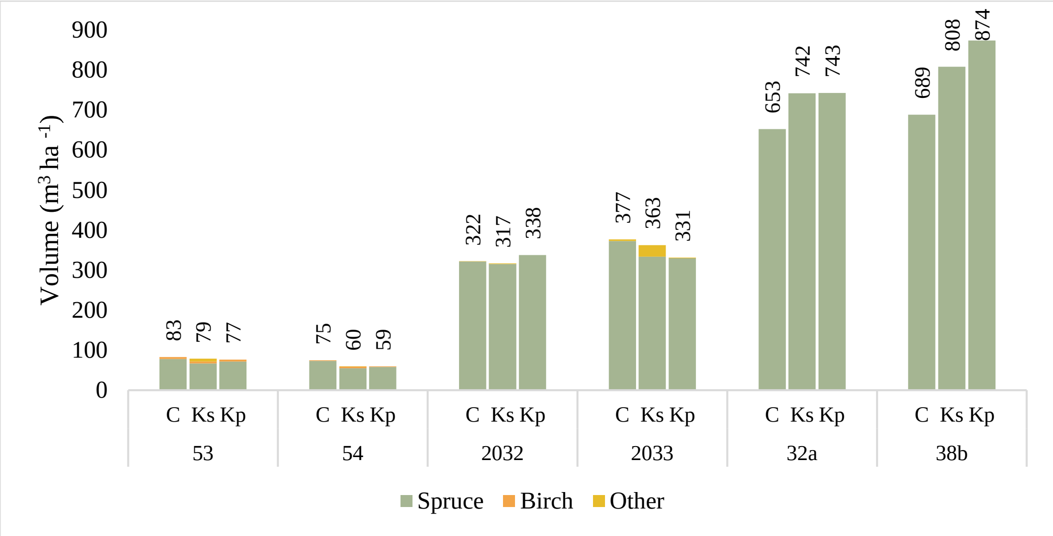


Figure 14. Volume comparison of different inventory methods in production stands. C - caliper method; Ks - Katam stand method; Kp - Katam sample plot method.

In both of the younger production stands Katam was underestimating the volume per hectare when comparing it to calipered data (Figure 14). In stand 53 the underestimation was 5% for Katam stand method and 7% for the sample plot method. In stand 54 the underestimations were 20% and 21%, respectively. In stand 2032 the volume estimated by Katam stand method was quite close to the value from calipered data (2% underestimation) and in stand 2033 stand method had a 4% underestimation and sample plot method a 12% underestimation of the volume when comparing to caliper method (Figure 14). In stand 32a the Katam stand and sample plot methods gave a fairly similar results to each other, but are overestimating the volume compared to the calipered data – 14% for both methods. In stand 38b both of the Katam methods used are also overestimating the volume values – 17% and 27% for Katam stand and for sample plot methods, respectively (Figure 14).

In the conservation stands there is no significant difference between volume per hectare values of the two different methods used ($p=0.444$). The volume per hectare estimates are between 301 to 536 $m^3 ha^{-1}$ according to calipered data and for Katam it ranges from 256 to 424 $m^3 ha^{-1}$ (Figure 15).

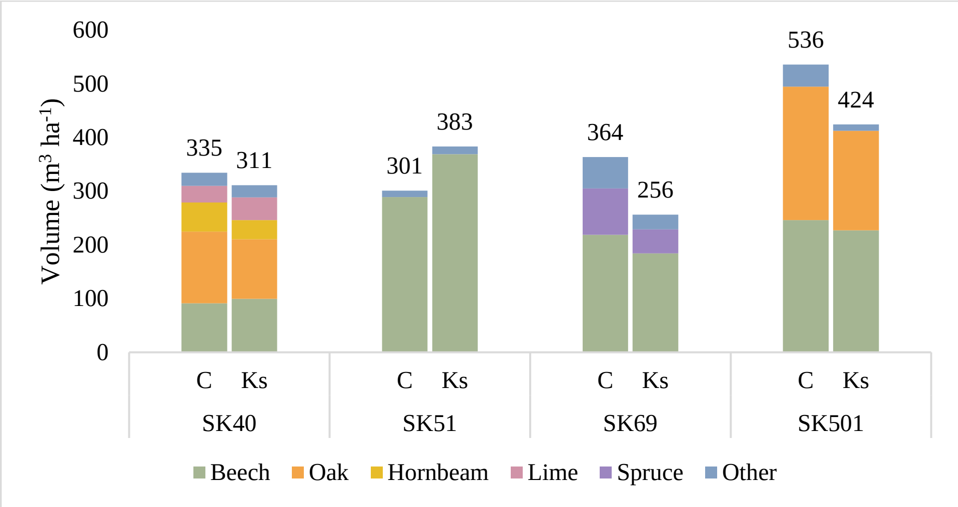


Figure 15. Volume comparison of different methods in conservation stands. C - caliper method; Ks - Katam stand method.

For stand SK40 Katam is underestimating the volume by 7%. In stands SK501 and SK69 Katam is underestimating the volume a lot, by 21% and 30% respectively. On the other hand, in stand SK51 Katam is overestimating volume by 27%. (Figure 15)

3.3.4. Stem density

In stem density results, there were no significant difference between the different inventory methods (p=0.3602) in the spruce production stands. The stem density per hectare values ranged from 558 to 1092 stems ha^{-1} according to the caliper method. According to Katam stand and sample plot methods it ranged from 564 to 901 stems ha^{-1} and from 532 to 974 stems ha^{-1}, respectively (Figure 16).

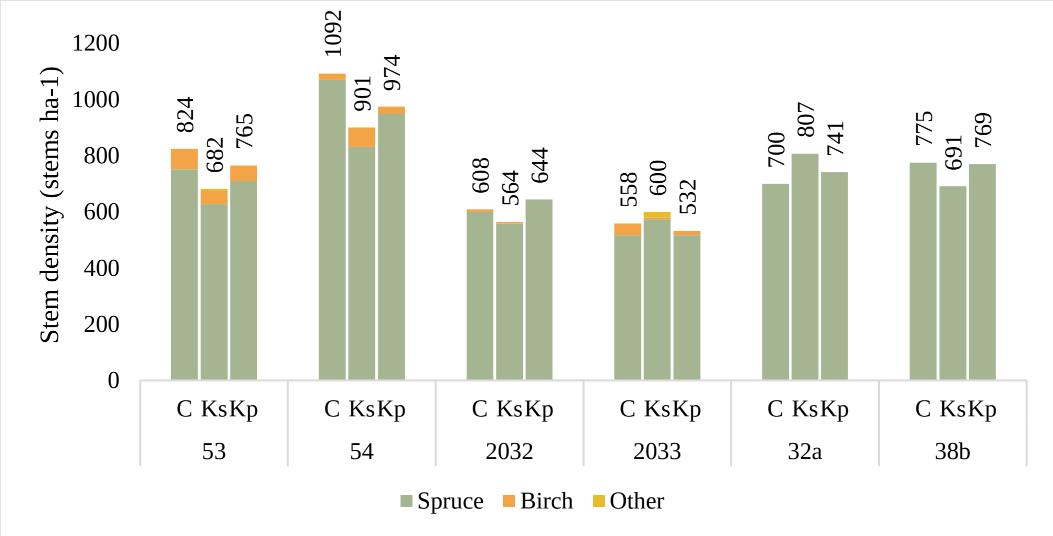


Figure 16. Density comparison of different methods in the production stands. C - caliper method; Ks - Katam stand method; Kp - Katam sample plot method.

In stands 53 and 54 both Katam methods used were underestimating the density when comparing it to caliper method. In stand 53 by 17% for Katam stand method and 7% for sample plot method and respectively 17% and 11% in stand 54. In stand 2032 Katam stand method underestimated stem density by 7% and Katam sample plot method overestimated the density by 6%. It was the opposite case for stand 2033 where Katam stand method overestimated stem density by 8% and Katam sample plot method underestimated stem density by 5%. In stand 32a Katam stand method overestimated stem density by 15% and the overestimation from Katam sample plot method was 6%. In stand 38b Katam underestimated the stem density by 11% for stand method and by less than 1% for sample plot method. (Figure 16)

There was no significant difference (p=0.249) between the two inventory methods in conservation stands. Stem density ranged from 192 to 703 stems ha^{-1} according to calipered data and from 269 to 538 stems ha^{-1} according to Katam (Figure 17).

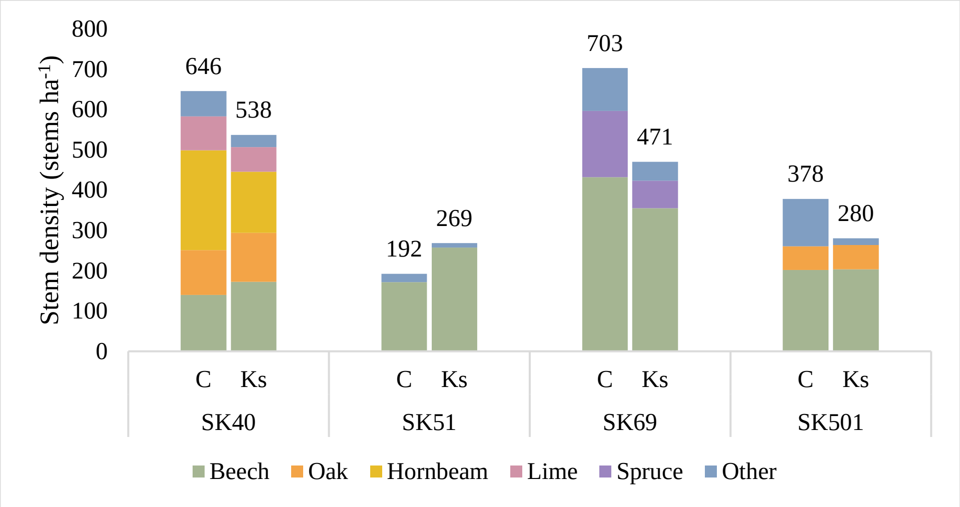


Figure 17. Density comparison of different methods in conservation stands. C - caliper method; Ks - Katam stand method.

Katam was underestimating the density for stand SK40 by 17%, SK69 by 33% and SK501 by 26%. On the other hand, it was overestimating the density of the stand SK51 by 40%. (Figure 17)

4. Discussion

4.1. What to consider when working with Katam^{TM} Forest

Katam is an inventory method which, as for all other techniques, needs some training before the operations run smoothly and time efficient. It does not work on all smart phones and the company's homepage https://www.katam.se/ should be consulted for which smart phones are suitable in order to use the app.

There are obstacles that can stop the algorithm from processing the video which need to be kept in mind when recording in order to refrain that from happening:

1. Branches or leaves brushing against the camera or getting too close to the camera;
2. Sun shining directly into the camera;
3. Video shaking too much due to difficult walking conditions or nearly falling.

Using Katam in the conservation stands was usually more difficult and manoeuvring around trees while recording takes a lot of time which makes the recordings longer. Therefore, it was discovered that the recordings should be kept below 2 minutes in length. Otherwise, it would take too long for the algorithm to process the recording and the application will most likely crash in the process and the recoding would not be processed at all.

In mixed forests some tree species might be hard to distinguish from each other just by assessing the information from the videos. That might lead to mistakes in tree species composition and therefore also the volume results of different species. It gets harder to recognize certain species the further away they are from the camera and that because of different light conditions and the video quality due to the camera on the phone. If possible, it would be reasonable for best results to already edit the tree species before leaving the stand, but that means processing the videos while in the forest.

By checking the processed videos, it was seen that Katam completely missed trees seldom and that mostly happened only for some stems on multi-stem trees or couple smaller diameter trees. This should not stop Katam from being used in conservation stands when the user is skilful with the application and knows its limits.

In conservation stands where there could be plenty of natural regeneration under the main canopy, the application should be used during months when trees have no leaves. Most likely after leafing out, the smaller trees would block the view of the phone camera under the canopy while taking recordings and influence the results negatively.

4.2. Katam™ Forest on single tree level

The higher RMSE in conservations stands when comparing to production stands indicates that Katam is much more accurate in stands with more homogenous structure and which have a more open structure with little undergrowth. That was also proven by comparing spruce RMSE to beech RMSE. It is especially one of conservation stands, SK501, that has a high RSME, this was also the stand with the largest trees. It could be discussed that since the heterogeneity in the conservation stands can almost be unlimited, some more studies could be useful before any decisions are made for the use of Katam in these stands.

Comparison of Katam estimated dbh to cross-calipered dbh showed that there seems to be a systematic underestimation in the lower diameter classes (Figure 8) which might be caused that smaller trees are harder to capture with the camera of the phone, but maybe more calibration is needed in with those trees. The underestimation was even worse for very large diameter classes (Figure 8), but it needs to be kept in mind the obviously the sample size for the larger diameter classes was much lower (Appendix 1 Table 6). As the application is made to be used in production forest then it is to be expected that it does larger errors with trees that are absent from a typical Swedish production forest. The opportunities to calibrate the application for larger trees that were encountered in the conservation stands included in this thesis, are limited in normal Swedish conditions. That might also be the main reason behind much higher RMSE in stand SK501 when comparing it to other conservation stands.

4.3. Accuracy of Katam™ Forest

There will always be different type errors when using various forest inventory methods. The aim is to develop the inventory method to remove systematic error making, in order to make the method more reliable. The results showed that there was no statistically significant difference in the estimation of mean dbh in the homogenous production stands of Norway spruce between different inventory methods. However, using Katam in the heterogenous conservation stands did not give the same estimate of mean dbh compared to calipered trees and was systematically overestimating the mean dbh.

Katam might have a problem of capturing smaller sized trees. That is shown especially by the diameter distributions of the 4 conservation stands where Katam is missing a lot of the trees from smaller diameter classes (Appendix 2; Figure 8). One of the reasons of underestimating the density of smaller trees might be that Katam is unable to recognise smaller trees if they are standing further away from the camera, but it's still able to recognize bigger trees from that distance. To some extent this can also be caused by the fact that Katam is difficult to use in a dense forest structure and those denser parts of stands with smaller trees will most likely be avoided in recordings.

Significant difference was also found in both types of forests for the shape parameter of the Weibull distribution function, but not for the scale parameter. For production stands the shape parameter of the Weibull function can be expected to be significantly different when comparing Katam stand method to caliper method, because normal Katam use on average covers a higher percentage of the stand which should give a better overview of the diameter distribution in the entire stand. In the homogenous production stands, which have gone through thinning(s), the scale parameter of the Weibull distribution, which shows the dbh range, should not vary that much even outside of the sample plots. Unless all the production stands have a lot of retention trees outside the sample plots, which in this case only stand 53 had (Appendix 2). The same results regardless of inventory methods for the conservation stands in the case of Weibull's scale parameter can be explained by that even though Katam is missing many smaller trees, it still could get the diameters from roughly the same range (Figure 11; Appendix 2).

Hypothesis was proven in the case of basal area, volume and stem density where no statistically significant difference was found in either 2 types of stands when comparing calipered results to Katam estimated results. That indicated that Katam does not systematically make errors in those 2 types of stands, but in some stands there still can be seen a large deviation from the caliper method which sometimes is underestimating and sometimes overestimating the basal area, volume and density results. For a better estimation of Katam accuracy, more studies which include a larger amount of stands with specific characteristics might be needed. That would provide an opportunity to calculate the RMSE for stand level estimates.

In the Norway spruce production stands 32a and 38b which were the oldest and still quite dense for that age, both methods of Katam showed a large overestimation comparing to calipered data. If it would have only been Katam stand method overestimation, then it might be that the average height calculated based on calipered sample plots did not correspond to the entire stand. That means, in the entire stand the mean height was lower, but by inserting the average height from sample plots, Katam calculates larger volume stock. But that doesn't explain the equally large overestimation in basal area which is not influenced by the manually measured stand height, but only by Katam own estimated dbh and recorded area. Nor does it explain the overestimation by the Katam sample plot method which mostly had the same trees based on which the height was calculated. Previous study has also shown an overestimation in older spruce forest (Andersson 2019). Therefore, it might be the case that Katam is not calibrated properly for those older stands with relatively large dbh and basal area. Opposite to the oldest production stands, there was a large underestimation of basal area and volume in stand 54 which is the densest and has the smallest mean dbh out all the production stands (Figure 16; Table 4). That might be caused by underestimation of trees in smaller diameter classes by Katam (Figure 8; Appendix 1 Table 6). An underestimation of diameter will become a bigger underestimation of basal area and volume.

Underestimation of dbh in lower diameter classes and missing smaller trees might explain some of the underestimation in basal area and volume of the 3 conservation stands that were underestimated. Although, for stands SK40, SK69 and SK501 the density percental underestimation is bigger than that of basal area or volume which also proves that smaller trees do not contribute that much to volume and basal area. Underestimation of the basal area and volume is most likely more explained by the underestimation of dbh in larger diameter classes by Katam. All those 3 stands have trees from really large diameter classes (Appendix 2) which is to be expected from heterogenous old growth stands set-aside for conservation. As those bigger trees contribute exponentially a lot more to the standing volume than smaller trees (Zianis *et al.* 2005), then underestimation of dbh will lead to an even bigger underestimation of volume of those single trees (Figure 8; Figure 9). If that underestimation is systematic, the stand volume will also be underestimated.

Stand SK51 is a heterogenous beech monoculture (Table 1; 11) and was the only one out of the conservation stand where the Katam results were overestimating density, basal area and volume. That might be caused by the fact that the entire stand was located on a steep slope and there it becomes more difficult for Katam to estimate the area of every recording. Katam might have underestimated the area, thus, overestimating the results. But it is difficult to estimate the accuracy of Katam recoding area estimation. This theory is supported by the fact that even though missing a lot of smaller diameter trees in the histogram (Figure 11), the Katam estimated stem density of the stand is still higher than the calipered density (Figure 17).

The production stands might be too varying in age and mean dbh to show a statistically significant difference between Katam and calipered data because there seems to be tendencies for Katam to have a certain error in different production stand ages. The number of sampled heterogenous conservation stands might be too small to show significant difference in those results.

4.3.1. Katam sample plot method

Only using Katam in sample plots gave basal area and volume results that are further away from calipered data comparing to Katam normal use. It might be expected that these results to be closer to calipered sample plot data, because most of the trees in the videos are the same as calipered. But that was the case only for stem density results.

Katam was not made to be used in this way and sometimes trying to fit the sample plot into the recordings was difficult and that especially in the circular plots in younger production stands, which might have influenced the results here. Also, using Katam normally (stand method) mostly allowed to capture a larger area of the stand and therefore give a better overview, which should always be preferred.

4.4. Novel technologies for forest inventories

The emerging novel technologies provide convenient ways to do a forest inventory and get the necessary data faster and cheaper comparing to conventional methods. But when using novel technologies, a cost-benefit analysis is needed in order to scrutinize how much accuracy in the acquired inventory data would be lost to cut down time and price of conducting an inventory. Therefore, even to this day conventional sample plot methodology is widely preferred because of the unwillingness of the forest owners/managers to lose on the accuracy of the results.

Mostly, when talking about novel technologies of conducting forest inventories, ALS (airborne laser scanning) comes up which has gone through continuous and large improvement over the last decades in both processing techniques and hardware used for it (Holopainen & Kalliovirta 2006; Surovy & Kuželka 2019). To the extent of deriving canopy height and density, ALS has been adopted into forest inventory methodologies on national or regional forest level in several countries (Sakari *et al.* 2014; Lindgren *et al.* 2015; Nilsson *et al.* 2017; Kangas *et al.* 2018; Magnussen *et al.* 2018). In the recent decade the most significant breakthrough has been the start of using unmanned aerial systems (UAS) and their rapid development for laser scanning or doing a DAP of the forest. Equipping drones with the necessary sensors, the forest inventory can be done on a finer spatial level and on a more accurate scale which provides a way for a better cost-benefit method of doing a forest inventory and will likely be used more and more in the upcoming years (Zhang *et al.* 2016; Surovy & Kuželka 2019).

Comparing Katam™ Forest to other novel forest inventory methods then its approach is to some extent simpler than the others and all what is needed is a smartphone with enough processing power. With enough accuracy the accessibility and simplicity should become the success of Katam, because it does not take much time for forest owners to do a forest inventory on a required smaller spatial scale.

4.4.1. Using Katam for forest inventories

Katam provides an easy way to capture a much larger part of stand more easily and quicker comparing to conventional forest inventory methods. One negative side of using Katam is that for best results there is still a need to insert height estimation which needs to be obtained by some other way. It can be done using conventional mehtods as were used in this thesis, it can be taken from remote sensing data or there is also an option to use Katam™ TreeMap which is another application from Katam Technologies AB and it uses a drone.

As Katam was made to be used in production forest, then it was expected it to give better results in the Norway spruce stands comparing to a heterogenous conservation stands. Nevertheless, the overestimation of results from stand 32a and 38b showed that the algorithm might still need some calibrating for those older production stands which are ripe for harvesting. This overestimation in older spruce stands was also shown in Andersson (2019) dissertation.

In theory the application is easy to use, but still needs a lot of practise beforehand to use it for best results. What SFA is trying to do with the application might work in experienced hands, as out of the conservation stands, the last stand to be inventoried with Katam was SK40 and that also gave the closest results to calipered results. But most likely, it is still too soon to fully start using the application in heterogenous conservation stands. The application needs some further development to be suitable for trees of much bigger dbh comparing to what one might find in a production forest. For now, getting the first estimate of stand characteristics by using Katam™ Forest would be a good option for the Swedish Forest Agency. Also, the processed videos from Katam would provide a solid way to archive the condition of the stand during the time when the deal was made between the landowner and SFA.

Smartphones have gone through massive improvement over the last 10 years and are still expected to get a lot better (Han & Cho 2016). The quality of Katam results also widely depends on the hardware of the smartphone (Katam n.d.). Therefore, it is to be expected that doing a forest inventory with methods such as Katam, which potentially only demand a use of a smartphone, will become more widely spread in the near future. Furthermore, as Katam is being constantly improved, saving the videos will allow to re-process them in the future and in theory the improved algorithm should give better estimates of the stand.

5. Conclusions

Combining Katam use with some other way to get height estimate of the stand will be a quick and convenient way for forest owners to get an estimate of standing volume in production stands. Previous experience in using the application is necessary to increase the accuracy of results. Further research into, if Katam is systematically overestimating older spruce stands is needed. And therefore, the application might need more calibrating for increased accuracy also in those stands.

However, it might be too soon to fully use the application in conservation stands which potentially could have trees with really large dbh with which the application seemed to struggle with. Further development into capturing the larger trees properly is needed and also not to miss or underestimate the trees from smaller diameter classes. Positive side of currently using Katam in set-aside reimbursements is that the videos produced will provide a solid proof of the status of the stand at the time of the deal.

This kind of technology is fairly easy to use and with the popularity of smart phones, also accessible to almost everyone. With further development and improvement, novel ways of doing a forest inventory could make conventional methods obsolete in the near future.

References

Andersson, E. (2019). *Noggrannhet och precision vid beståndsuppskattning av mobilapplikationen KATAM.* Diss. Kalmar: Linneuniversitetet.

Baker, S.R., Bloom, N., Davis, S.J. and Terry, S.J. (2020). *Covid-induced economic uncertainty* (No. w26983). National Bureau of Economic Research.

Beine, M., Bertoli, S., Chen, S., D'Ambrosio, C., Docquier, F., Dupuy, A., … and Koulovatianos, C. (2020). Economic effects of Covid-19 in Luxembourg. Available at: https://www.liser.lu/documents/RECOVID/RECOVid_working-note_full-1.pdf

Bergh, J., Johansson, U., Ekö, P. M. and Snygg, G. (2019). *Test av Katam systemet för uppskattning av beståndsdata i långsiktiga skogliga fältförsök i sydvästra Sverige.* (Unpublished).

Bjärstig, T., Sandström, C., Sjögren, J., Soneson, J. and Nordin, A. (2019). A struggling collaborative process–revisiting the woodland key habitat concept in Swedish forests. *Scandinavian Journal of Forest Research*, vol. 34, pp. 699-708.

Brandel, G. (1990). *Volymfunktioner för enskilda träd. Tall, gran och björk.* Sveriges lantbruksuniversitet, Institutionen för skogsproduktion. (Rapport, 1990:26), pp. 1-181.

Burkhart H.E., Tomé M. (2012). Diameter-distribution models for even-aged stands. In: Modeling Forest Trees and Stands. Springer, Dordrecht.

Delignette-Muller, M.L. and Dutang, C. (2015). fitdistrplus: An R package for fitting distributions. *Journal of Statistical Software*, vol. 64, pp. 1-34.

Dick, A. R., Kershaw Jr, J. A., and MacLean, D. A. (2010). Spatial tree mapping using photography. *Northern Journal of Applied Forestry*, vol. 27, pp. 68-74.

Eggers, J., Lindhagen, A., Lind, T., Lämås, T. and Öhman, K. (2018). Balancing landscape-level forest management between recreation and wood production. *Urban Forestry & Urban Greening*, vol. 33, pp. 1-11.

Felton, A., Petersson, L., Nilsson, O., Witzell, J., Cleary, M., Felton, A. M., … and Nilsson, U. (2019). The tree species matters: Biodiversity and ecosystem service implications of replacing Scots pine production stands with Norway spruce. *Ambio*, vol. 49, pp. 1035-1049.

Goodbody, T.R., Coops, N.C., Marshall, P.L., Tompalski, P. and Crawford, P. (2017). Unmanned aerial systems for precision forest inventory purposes: A review and case study. *The Forestry Chronicle*, vol. 93, pp. 71-81.

Grönlund, Ö., Erlandsson, E., Djupström, L., Bergström, D. and Eliasson, L. (2020). Nature conservation management in voluntary set-aside forests in Sweden: practices, incentives and barriers. *Scandinavian Journal of Forest Research*, vol. 35 (1-2), pp. 96-107.

Hagberg, E. and Matérn, B. (1975). *Tabeller för kubering av ek och bok.* Skogshögskolan, Inst. f. skoglig matematisk statistik, (Rapport, 14). Stockholm.

Han, Q. and Cho, D. (2016). Characterizing the technological evolution of smartphones: insights from performance benchmarks. *Proceedings of the 18th Annual International Conference on Electronic Commerce: e-Commerce in Smart Connected World*, pp. 1-8.

Holmgren, J., Tulldahl, M., Nordlöf, J., Willén, E., and Olsson, H. (2019). Mobile laser scanning for estimating tree stem diameter using segmentation and tree spine calibration. *Remote Sensing*, vol. 11, p. 2781.

Holopainen, M. and Kalliovirta, J. (2006). Modern data acquisition for forest inventories. *Forest Inventory*, pp. 343-362. Springer, Dordrecht.

Kangas, A., Astrup, R., Breidenbach, J., Fridman, J., Gobakken, T., Korhonen, K.T., ... and Olsson, H. (2018). Remote sensing and forest inventories in Nordic countries–roadmap for the future. *Scandinavian Journal of Forest Research*, vol. 33, pp. 397-412.

Katam. (n.d.). *KATAM™ Forest.* Available at: https://www.katam.se/products/forest/ [23.03.2020].

Knoke, T., Ammer, C., Stimm, B. and Mosandl, R. (2008). Admixing broadleaved to coniferous tree species: a review on yield, ecological stability and economics. *European journal of forest research*, vol. 127, pp. 89-101.

Liang, X., Wang, Y., Pyörälä, J., Lehtomäki, M., Yu, X., Kaartinen, H., ... and Vaaja, M. (2019). Forest in situ observations using unmanned aerial vehicle as an alternative of terrestrial measurements. *Forest Ecosystems*, vol. 6, pp. 1-16.

Lindbladh, M. and Foster, D.R. (2010). Dynamics of long-lived foundation species: the history of *Quercus* in southern Scandinavia. *Journal of Ecology*, vol. 98, pp. 1330-1345.

Lindbladh, M., Niklasson, M., Karlsson, M., Björkman, L. and Churski, M. (2008). Close anthropogenic control of *Fagus sylvatica* establishment and expansion in a Swedish protected landscape–implications for forest history and conservation. *Journal of Biogeography*, vol. 35, pp. 682-697.

Lindgren, N., Christensen, P., Nilsson, B., Åkerholm, M., Allard, A., Reese, H. and Olsson, H. (2015). Using optical satellite data and airborne lidar data for a Nationwide Sampling Survey. *Remote Sensing*, vol. 7, pp. 4253-4267.

Magnussen, S., Nord-Larsen, T. and Riis-Nielsen, T. (2018). Lidar supported estimators of wood volume and aboveground biomass from the Danish national forest inventory (2012–2016). *Remote Sensing of Environment*, vol. 211, pp. 146-153.

Maltamo, M., Malinen, J., Packalén, P., Suvanto, A. and Kangas, J. (2006). Nonparametric estimation of stem volume using airborne laser scanning, aerial photography, and stand-register data. *Canadian Journal of Forest Research*, vol. 36, pp. 426-436.

Mäntymaa, E., Juutinen, A., Mönkkönen, M. and Svento, R. (2009). Participation and compensation claims in voluntary forest conservation: A case of privately owned forests in Finland. *Forest Policy and Economics*, vol. 11, pp. 498-507.

Nilsson, M., Nordkvist, K., Jonzén, J., Lindgren, N., Axensten, P., Wallerman, J., Egberth, M., Larsson, S., Nilsson, L., Eriksson, J. and Olsson, H. (2017). A nationwide forest attribute map of Sweden predicted using airborne laser scanning data and field data from the National Forest Inventory. *Remote Sensing of Environment*, vol. 194, pp. 447-454.

Nitare, J., 1992. Woodland key-habitats of rare and endangered species will be mapped in a new project of the Swedish National Board of Forestry. *Svensk Botanisk Tidskrift*, vol. 86, pp. 219-226.

Noordermeer, L., Bollandsås, O.M., Ørka, H.O., Næsset, E. and Gobakken, T. (2019). Comparing the accuracies of forest attributes predicted from airborne laser

scanning and digital aerial photogrammetry in operational forest inventories. *Remote Sensing of Environment*, vol. 226, pp. 26-37.
Näslund, M. (1936). Skogsförsöksanstaltens gallringsförsök I tallskog. (Meddelande från statens skogsförsöksanstalt 29).
Paliogiannis, C., Cliquet, A. and Koedam, N. (2019). The impact of the economic crisis on the implementation of the EU Nature Directives in Greece: An expert-based view. *Journal for Nature Conservation*, vol. 48, pp. 36-46.
R Core Team. (2019). R: A language and environment for statistical computing. *R Foundation for Statistical Computing*, Vienna, Austria. Available from https://www.r-project.org/.
RStudio Team. (2016). RStudio: Integrated Development for R. *RStudio, Inc.*, Boston, MA. Available from http://www.rstudio.com/.
Sakari, T., Juho, P., Andras, B., Hyvönen, P., and Eero, M. (2014). NFI plots as complementary reference data in forest inventory based on airborne laser scanning and aerial photography in Finland. *Silva Fennica*, vol. 48, p. 983.
Siipilehto, J. (2000). A comparison of two parameter prediction methods for stand structure in Finland. *Silva Fennica* vol. 34, pp. 331-349.
Surový, P. and Kuželka, K. (2019). Acquisition of forest attributes for decision support at the forest enterprise level using remote-sensing techniques – A review. *Forests*, vol. 10, p. 273.
Thrun, S. (2007). Simultaneous localization and mapping. *Robotics and cognitive approaches to spatial mapping*, pp. 13-41. Springer, Berlin, Heidelberg.
Timonen, J., Gustafsson, L., Kotiaho, J.S. and Mönkkönen, M. (2011). Hotspots in cold climate: conservation value of woodland key habitats in boreal forests. *Biological Conservation*, vol. 144, pp. 2061-2067.
Vastaranta, M., Holopainen, M., Yu, X., Hyyppä, J., Hyyppä, H. and Viitala, R. (2011). Predicting stand-thinning maturity from airborne laser scanning data. *Scandinavian Journal of Forest Research*, vol. 26, pp. 187-196.
Weibull, W. (1951). Wide applicability. *Journal of Applied Mechanics*, vol. 103, pp. 293-297.
White, J.C., Coops, N.C., Wulder, M.A., Vastaranta, M., Hilker, T. and Tompalski, P. (2016). Remote sensing technologies for enhancing forest inventories: A review. *Canadian Journal of Remote Sensing*, vol. 42, pp. 619-641.
Widman, U. (2016). Exploring the role of public–private partnerships in forest protection. *Sustainability*, vol. 8, pp. 1-15.
Wu, J., Leng, C., Wang, Y., Hu, Q. and Cheng, J. (2016). Quantized convolutional neural networks for mobile devices. *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 4820-4828.
Zhang, J., Hu, J., Lian, J., Fan, Z., Ouyang, X. and Ye, W. (2016). Seeing the forest from drones: Testing the potential of lightweight drones as a tool for long-term forest monitoring. *Biological Conservation*, vol. 198, pp. 60-69.
Zianis, D., Muukkonen, P., Mäkipää, R. and Mencuccini, M. (2005). Biomass and stem volume equations for tree species in Europe. *Silva Fennica*, vol. 4, pp. 1-63.

Acknowledgements

I would like to thank the team of Katam Technologies AB who provided me with a suitable mobile phone and Katam™ Forest application to be used in this thesis. They taught me about how the application works and how to use it and were always willing to answer my questions about different functions of the application. I would also like to thank the Swedish Forest Agency who provided me with the inventoried tree-lists from the conservation areas.

Writing this thesis would have been impossible without the continued advice, assistance and support from my supervisor Emma Holmström. This master's thesis project was funded by Partnerskap Alnarp.

Appendix 1 – Additional tables

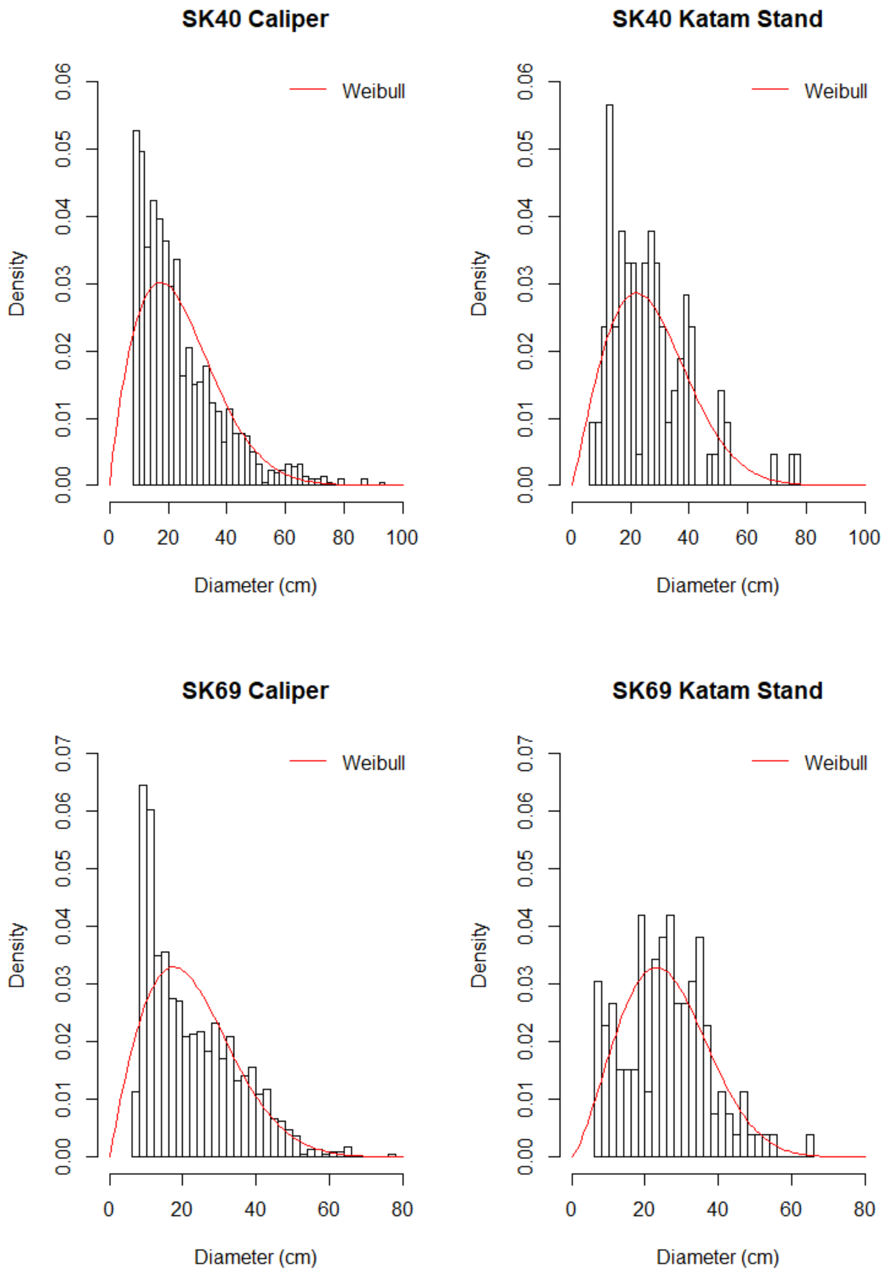
Table 5. Different parameter values for Näslund's height curves

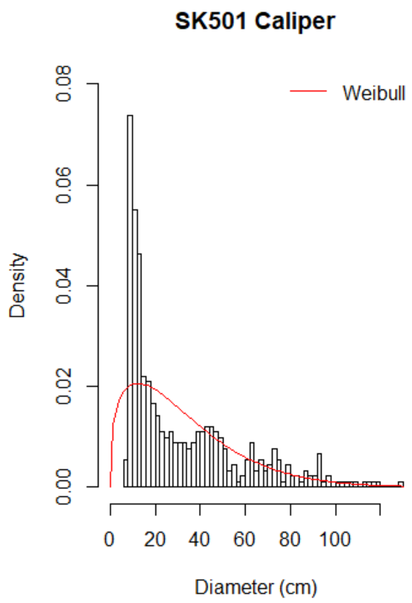
Stand no.	Species	β_0	β_1	α
53	spruce	0.4918153	0.1643065	3
53	birch	0.1884696	0.07262183	2
54	spruce	0.5917638	0.1594012	3
54	birch	0.1249986	0.07978431	2
2032	spruce	6.188306	0.1330372	3
2033	spruce	8.621692	0.1330372	3
32a	spruce	4.580395	0.1414371	3
38b	spruce	6.422086	0.1351285	3
SK69	spruce	9.452496717	0.133301719	3
SK40	hornbeam	5.116100861	0.053533958	2
SK40	lime	0.721413235	0.002581277	1
SK501	beech	13.87006914	0.094353588	2
SK69	beech	10.16722153	0.096487104	2
SK51	beech	10.04708018	0.09785512	2
SK40	beech	15.08478674	0.092533939	2
SK501	oak	21.94660981	0.507608858	5
SK40	oak	14.01107048	0.510023163	5

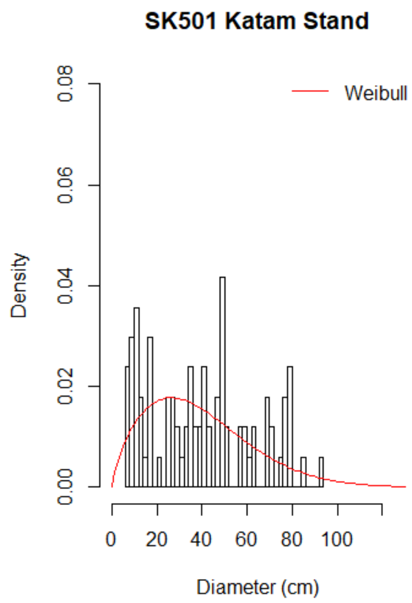
Table 6. Estimation with Katam of dbh and volume on average in 10 cm diameter classes compared to "caliper data", in %.

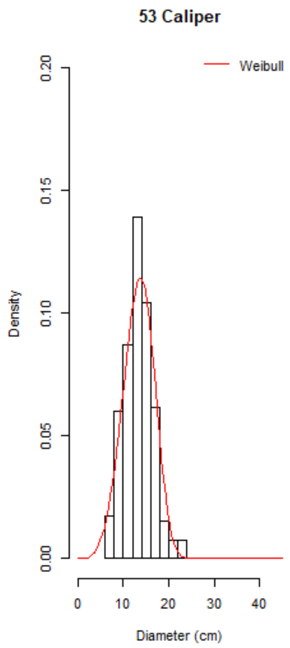
Diameter class (cm)	Range of diameter class (cm)	DBH %	Volume %	No. of trees
10	0-9	87	75	4
20	10-19	90	87	131
30	20-29	97	95	61
40	30-39	99	97	56
50	40-49	99	98	27
60	50-59	99	89	14
70	60-69	98	88	10
80	70-79	99	94	4
90	80-89	83	62	4
100	90-99	70	49	3
	Mean deviation from 100%	8	17	

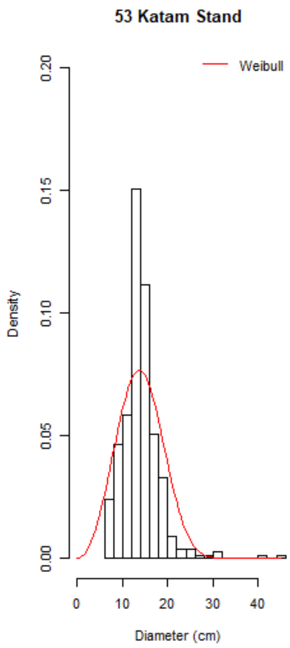
Appendix 2 – Stand theoretical densities of diameter distributions per different inventory methods

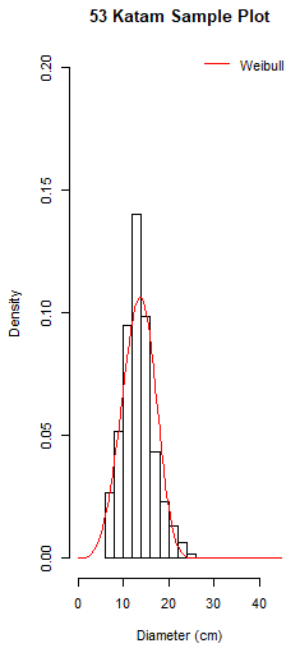


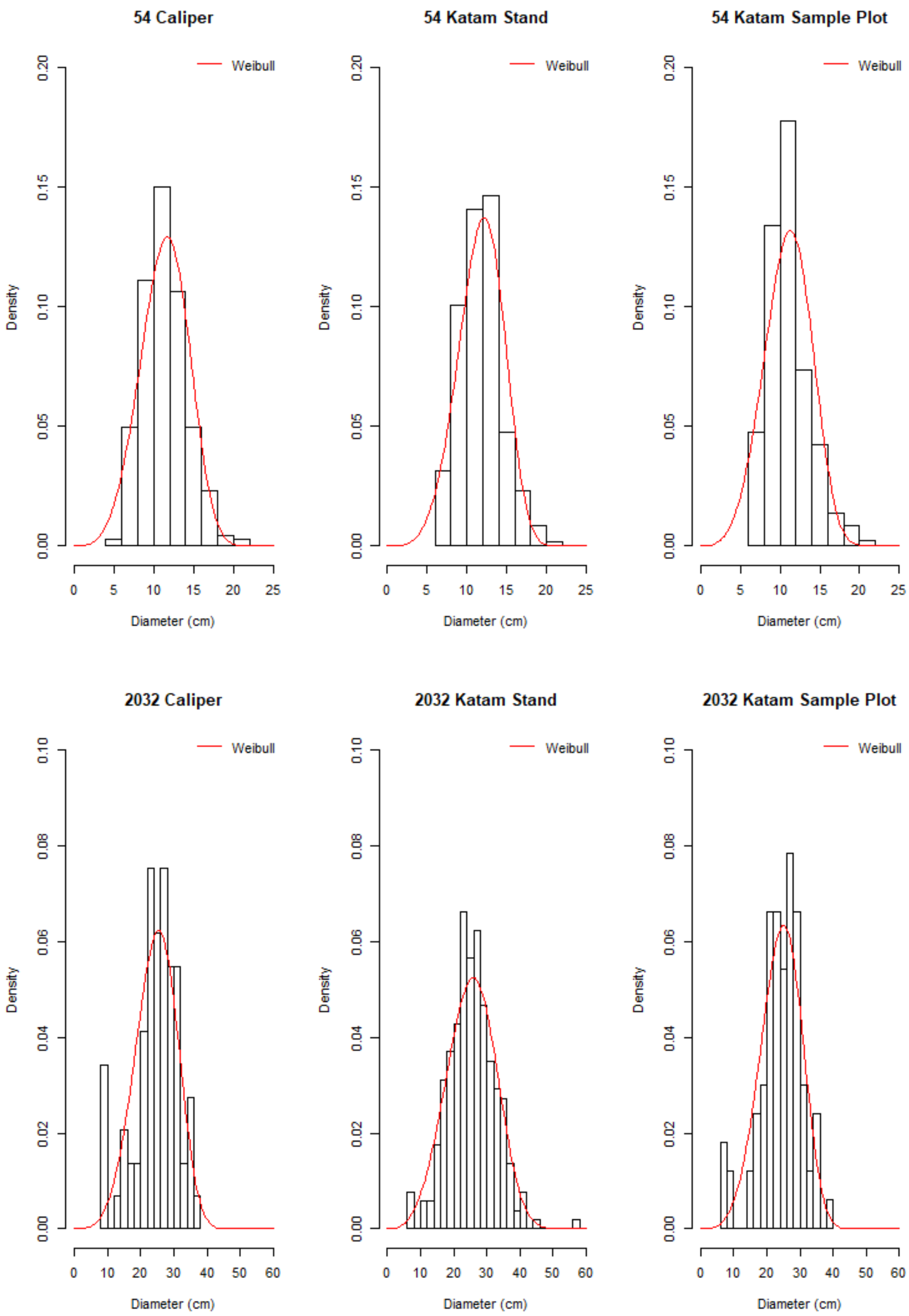

SK501 Caliper
Weibull
Density
0.00
0.02
0.04
0.06
0.08
0
20
40
60
80
100
Diameter (cm)

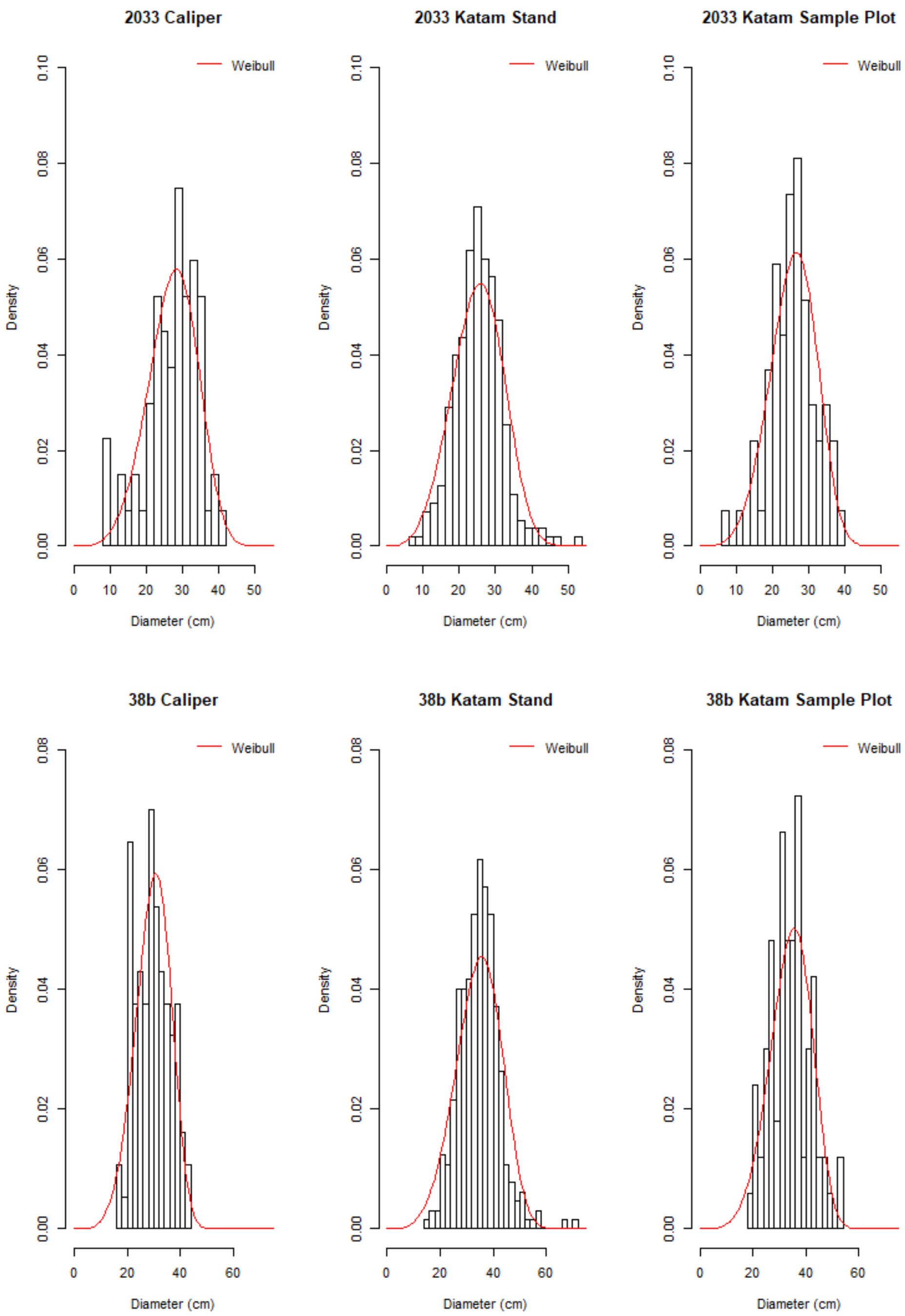

SK501 Katam Stand
Weibull
Density
0.00
0.02
0.04
0.06
0.08
0
20
40
60
80
100
Diameter (cm)


53 Caliper
Weibull
Density
0.00
0.05
0.10
0.15
0.20
0
10
20
30
40
Diameter (cm)


53 Katam Stand
Weibull
Density
0.00
0.05
0.10
0.15
0.20
0
10
20
30
40
Diameter (cm)


53 Katam Sample Plot
Weibull
Density
0.00
0.05
0.10
0.15
0.20
0
10
20
30
40
Diameter (cm)


54 Caliper
54 Katam Stand
54 Katam Sample Plot
2032 Caliper
2032 Katam Stand
2032 Katam Sample Plot
Weibull
Density
Diameter (cm)


2033 Caliper
2033 Katam Stand
2033 Katam Sample Plot
38b Caliper
38b Katam Stand
38b Katam Sample Plot
Weibull
Density
Diameter (cm)