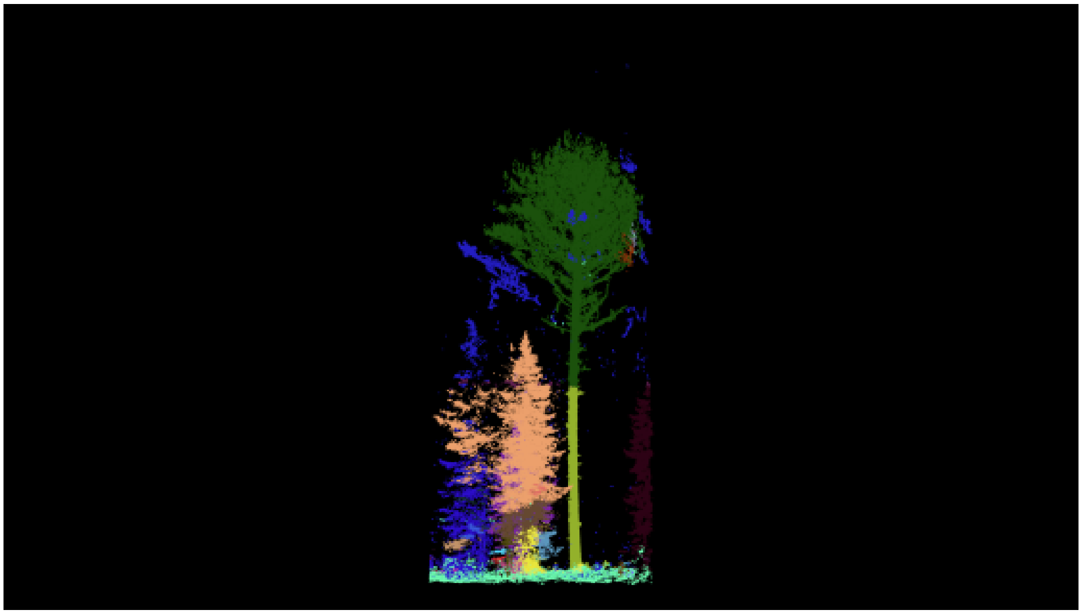
DETERMINING THE ACCURACY OF TERRESTRIAL LIDAR ON RED PINE

By:

Emily Pollington



FACULTY OF NATURAL RESOURCES MANAGEMENT
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DETERMINING THE ACCURACY OF TERRESTRIAL LIDAR ON RED PINE

By:

Emily Pollington

An undergraduate thesis submitted in
partial fulfillment of the requirements for the
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Ulf Runesson

Alex Bilyk

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ABSTRACT

This paper reviews the capabilities of the FARO Terrestrial LiDAR technology to produce accurate forest measurements. The study was conducted on single Red Pine trees in Northern Ontario. Field measurements were compared to scanned terrestrial LiDAR data. Results found that the FARO was accurate in producing tree heights. When determining diameter at breast height (DBH) and volume, there is still research that needs to be done. There was error due to target placement which distorted diameter at breast height measurements. With the proper training, better results could be omitted using terrestrial LiDAR. Terrestrial LiDAR has the potential to replace traditional field methods and technology is advancing very quickly. This study is important in order to update current forest measurement methods and produce faster, more accurate results. It is hoped that this study will inform foresters and researchers about the potential uses for terrestrial LiDAR in the forest stand environment.

ACKNOWLEDGMENTS

I would like to acknowledge and recognize the substantial help from Chris Stratton at the MNR, and his growth and yield crew, for helping to collect the manual stem analysis information and terrestrial LiDAR scan data for this thesis. As well as Chris for helping to provide direction, advice and knowledge throughout the process. In addition, I would like to thank Alex Bilyk for being my lead role model in this thesis, that is also a small part of his PhD. Alex was able to help in many ways such as guidance, direction, knowledge, advice, and teaching me the new software. As well, Alex Bilyk was also my second reader and provided lots of direction for the written portion of my thesis. I would like to acknowledge Ulf Runnesson, my thesis supervisor for helping guide my topic and for providing direction and feedback. I would like to acknowledge Frank Lukai and Jesse Humphrey for guidance in my volume calculations. Lastly, Dr. Ashley Thomson for editing my final thesis draft.

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INTRODUCTION

The advancement of technology is very important for the assurance of accurate and quality data collection in the forest sector. Terrestrial LiDAR is a new and upcoming technology. It is used for close-range, high-accuracy scanning. This technology provides three-dimensional images similar to those provided by aerial LiDAR systems, but instead, uses a laser to map objects from distances of 1 to 100 metres on the ground rather than from an airplane.

This machine is fast, straight forward and provides an accurate three-dimensional model of the scanned scene. Once scanned, the three-dimensional point cloud is imported into the software "CloudCompare" and "3D Forest" for further analysis. Until now, the machine has been used mainly for buildings, crash scenes and construction sites. It is important that the machine is now tested on trees and then stands to determine accuracy and quality, in order to aid in forest technicians and in estimating tree growth to project growth and yield, which would be used in the prediction of future stand and forest volume, biomass and carbon content.

Stem analysis is an important tool in the forest sector, it aids in collecting data to monitor and investigate a number of characteristics of managed stands such as: stem profile (taper), rate of diameter and height growth, wood and fibre properties, and site index. However, manual stem analysis is a form of destructive sampling. Therefore, succeeding measurements are not possible. While, FARO, might eliminate the need for destructive sampling, it is still a relatively new technology and has not been evaluated for its utility and accuracy in stem analysis. Thus, the purpose of this thesis is to determine the accuracy of the FARO technology for determining the outside total volume of the tree and other parameters such as DBH, height and taper. The null hypothesis states that the FARO will not be able to accurately estimate the volume of a tree. Further statistical analysis, using T-tests will show any variation in the two samples; LiDAR and manual. This information is highly valuable for the OMNRF and other forest companies, since it would save time and money when assessing stand quality and monitoring if terrestrial LiDAR is accurate. As well as aid in more accurate prediction of the future forest stand and volume.

Forest inventory and data collection must begin to change with the advancements in technology. This will allow for more accurate and faster data collection which will aid in the future of forest predictions by being able to scan entire forest stands and permanent sample plots for research. If the FARO is able to accurately determine the outside total volume of the tree, further research will be needed to develop methods to determine the inside volume for use in true stand volume analysis.

LITERATURE REVIEW

FOREST INVENTORY

Forests are an important natural resource that require monitoring and analysing for sustainability and management. Assessing the spatial organisation of trees within the forest is a key objective for both forest managers and researchers. Proper management of forests play an important role in ecological and economic development. For this purpose, forest inventory is essential. Forest inventory provides comprehensive information about the state and dynamics of forests (Aijazi et al. 2017). This involves measuring structural parameters on a sample of trees to assess their variability at the plot scale, together with the spatial position of stems and crowns and tree species identification (Dassot et al. 2011). These parameters include diameter at breast height (DBH), tree height (h), species, basal area and volume, which are critical to obtaining aboveground biomass, calculating forest ecosystem services and assessing carbon sequestration strategies for sustainable management (Moskal and Zheng 2012). Different attributes are studied and measured for both ecological benefits and economic reasons.

Forest inventory has facilitated studies and research not only regarding the economic aspects of forest management, such as timber product sale or revenue earnings (Thony et al. 2006); but also the ecological aspects including wildlife habitat (Cottone and Ettle 2001), forest stability, ecosystem services (Patenaude 2005) and natural biodiversity conservation (Kim et al. 2009). Most traditional forest structure mensuration methods using digital hemisphere photographs and range finders cannot capture the 3-D structural information for the single tree and forest stand (Moskal and Zheng 2012). Therefore, the FARO could play an important role in filling the gap for three-dimensional forest models and inventory.

STEM ANALYSIS

Detailed stem measurements provide a means of assessing volume in a stand and understanding relationships involving tree growth, allometry, stem mechanics, and canopy structure (Moskal and Zheng 2012). One stem measurement, the DBH, is an important forest inventory parameter, and is the basic and common parameter in tree allometry, basal area, and volume estimation. DBH is also an important aspect for ecosystem services assessment because it provides information about the stand structure, state of stand development, and aids in sivilculture prescriptions. Calipers and diameter tape are the traditional tools to take this measurement. Basal area is the cross-sectional area of a tree measured at breast height. It is very important for forest management because it is related to many ecological parameters such as site density and stand's volume. A key piece of information when analysing LiDAR data will be ensuring the accuracy of producing a DBH in the correct DBH Class, 2 cm increments.

Methods for measuring tree stem volume fall into two broad categories: direct and indirect methods (Moskal and Zheng 2012). Fluid displacement is one of the direct methods, which works by placing the stem into water and measuring the volume of displaced water. Although accurate, this method involves extensive labor and destructive sampling. Standard sectional method is the most common and popular method. By sectioning the stem into a number of lengths, the dimensions of each section are measured, after calculating the section volumes, the whole stem volume is obtained by summation. In addition, the taper steps, graphical, and taper lines are also alternatives for measuring tree volume.

INTRODUCING TERRESTRIAL LIDAR

Forest mensuration has traditionally been based on plot-scaled ground-based manual measurements. Wood volumes have historically been estimated by foresters using standard measurements of tree height and stem diameter at breast height (DBH) with models that make it possible to estimate the total volume (Baskerville 1974). However, these equations are not the best for single-tree assessment that include the crown compartment and can lead to large errors in volume estimates. Nowadays, foresters need accurate and detailed descriptions of the characteristics of trees such as stem profile and branch biomass (Dassot et al. 2011). However, obtaining this information in the forest environment today is time-consuming, labour-intensive and often destructive when traditional methods that are based on human estimation and experience are used (Dassot et al. 2011, Aijazi et al. 2017). While lack of automation makes these uses expensive and subjective. As well, studies show that current forest inventories based on allometric relationships from standard measurements of heights and diameters at breast height (DBH) generally lead to large errors, especially in commercial volume estimates (Dassot et al. 2011).

Forestry is becoming a more precise science and now requires additional parameters linked to the tree structure (stem shape, quality, branch biomass, leaf area index) at different spatial scales and higher resolution (Kint et al. 2009). In order to achieve this, foresters have recently become interested in technologies such as terrestrial Light Detection And Ranging (LiDAR) scanning, commonly referred to as terrestrial laser scanning (TLS), which has great potential for rapid, detailed and accurate forest structure modeling (Dassot et al. 2011). The use of terrestrial LiDAR scanners in forest environments is being studied extensively due to the high potential of this technology to acquire three-dimensional data on standing trees rapidly and accurately (Dassot et al. 2011). Since 2003, both the capabilities of the devices and data processing technology have improved significantly, with encouraging results. Terrestrial LiDAR has been applied to forest inventory measurements (plot cartography, species recognition, diameter at breast height, tree height, stem density, basal area and plot-level wood volume estimates) and canopy characterisation (virtual projections, gap fraction and three-dimensional foliage distribution) (Dassot et al. 2011). This form of measurement is also being used for stand value and wood quality assessment. Terrestrial LiDAR provides new support for ecological applications such as the assessment of the physical properties of leaves, transpiration processes and microhabitat diversity (Dassot et al. 2011).

TREE VOLUME

Tree volume is an essential measurement when managing a forest for commercial timber production. Volume estimate is also important for determining biomass of the forest, the amount of carbon storage, fuel sources etc. Directly or indirectly, the estimate is based on the volumes of individual trees. Therefore, the estimation of stem volume is an important aspect of forest mensuration. Usually volume is expressed inside bark and according to different specifications. For this thesis, outside bark is used because LiDAR is not capable of producing bark measurements. A few past studies have been done to look into the accuracy of terrestrial LiDAR on different tree species and many agriculture scenarios. Tumbo et al. (2002) compared the performance of ground ultrasonic and laser sensors for measuring citrus canopy volume obtaining good correlations with manual data. In Ehlert et al. (2008), the relationship between LIDAR measurements and crop biomass density was compared under field conditions with very good correlations. . In Rosell et al. (2009), the volume estimate obtained with a LIDAR was correlated with manual measurements of the volume obtaining good correlations (R2 = 0.97). Good correlations (R2 > 0.8) were also obtained with manual measurements of the foliage surface for pear, apple, and citrus orchards and vineyards.

Wei and Salyani (2005) used a terrestrial LiDAR to measure tree height, width and volume, giving a coefficient of variation of 5.4% and a relative error of 4.4% in the estimation of the volume of the trees.

One disadvantage of tree volume estimates in a forest scenario compared to an agriculture crop is that it cannot be easily georeferenced using the trees as landmarks since there is too much noise from surrounding trees. Therefore, target landmarks must be set up in the field to be referenced from the scanner. Two main factors affect the tree volume estimate from the raw data obtained with a moving terrestrial LiDAR: the uncertainty in the set of distances measured and the uncertainty in the 3D positioning of the reference axis of the scan (Palleja et al. 2010).

PAST STUDIES

There have been many studies using ALS (airborne laser scanning) to measure forest height, individual tree height, crown diameter and mapping of forested areas. Since 2001, as a complement to traditional measurements, ALS technology has been used to rapidly describe forest structure over large areas (Dassot et al. 2011). It makes it possible to collect information of use for forest inventories (tree location within plots, tree height, crown dimensions and volume estimates), as well as for forest ecology (vertical forest stratification, gas exchanges, transpiration and canopy carbon content). However, airborne LiDAR scanning provides limited information at the tree scale or under the canopy, which is required for certain forest applications and wood volume prediction.

Terrestrial LiDAR (TLS) technologies have therefore been implemented to obtain detailed information at the tree or plot scales. Terrestrial laser scanners provide a more effective solution for obtaining detailed understory information important when estimating different tree parameters. Both static and mobile systems provide millions of three-dimensional points from inside the forest at close range (Aijazi et al. 2017). The first studies conducted on TLS were aimed at tree structure assessment using TLS scanners focused on characterising standard dendrometry parameters, i.e. stem diameters, tree height, stem density, basal area and commercial wood volumes. They aimed at demonstrating the potential of TLS scanning for faster and more accurate measurements compared to traditional field inventories. These studies aimed at comparing wood volume TLS measurements to manual measurements are rare and mainly focused on small plants under controlled conditions (Keightley and Bawden, 2010).

For example, Watt and Donoghue (2005) compared the field measurements of DBH and tree height with the results from TLS-based measurements. Their results indicated that occlusion was a great factor affecting the information obtained by the TLS. Tansey et al. (2009) explored the feasibility of TLS based automatic methods to estimate the DBH in a forest environment with high stand density and found a method to automate the stem mapping process. Huang (2010) presented an automated method for measuring DBH and tree heights with a TLS. Many other studies have tried to extract DBH information from TLS data, but research is limited to thinned stands (Murphy 2008), limited species (Omasa et al. 2002) and limited samples (Lovell et al. 2011).

Other studies have been done to reconstruct trees from TLS data. Some use a method to fit cylinders into multiple scan mode point clouds to model the tree trunk (Aijazi et al. 2017). These studies demonstrate the potential of TLS to characterise the woody structure of trees. However, they focus on modeling and visualizing trees rather than the estimation of tree parameters and are prone to errors when determining accurate tree parameters. Concerning the modelling method, the review of the literature revealed the appropriateness of cylinder fitting for assessing the taper of the main tree stem, but without volume comparison (Thies et al. 2004).

During the last decade, the major part of the research on TLS in the forest environment focused on developing automated algorithms for plot-scaled forest inventories, i.e., DBH and tree height estimates (Hopkinson et al. 2004; Tansey et al., 2009). Bienert et al. (2007) provided a complete set of algorithms allowing for stem segmentation, diameter fitting for the observed portion of the stem and for the non-observable stem heights. The TreeMetrics Company aggregated the algorithms described in Bienert et al. (2007) in the AutoStemTM software (Keane 2007). This then made it possible to automatically or manually process point clouds by recording diameters along tree stems at variable height intervals, leading to the calculation of plot-level stem volumes. AutoStemTM was used by Murphy (2008) to determine the value of Douglas fir stands.

Forests are complex which sometimes aren't suitable for automated algorithms due to the noise that can occur in the TLS data and the accuracy of the reference measurements themselves. A few studies have shown that TLS is unsuccessful in determining tree heights compared to ALS and ground measurements. Hopkinson et al.

(2004) demonstrated in their study that LiDAR data underestimated mean plot-level tree height by about 1.5 m compared to the ground manual field measurements. Higher error levels in diameter estimation were found in the upper part of tree crowns because of the poor description of the stem caused by branches in the foreground (Henning and Radtke 2006). The use of T-LiDAR scanners remains a technological challenge in forest environments because of the structural complexity of forests.

PROS AND CONS OF TERRESTRIAL LIDAR

Terrestrial LiDAR scanners provide non-destructive, accurate and extensive information about forest structure that is difficult or impossible to obtain using traditional methods. Forest inventories should take advantage of the new possibilities offered by these instruments to rapidly assess plot-level stem profiles and shapes, and understorey characteristics (Loudermilk et al. 2009). Their non-destructive measurements make it possible to freeze information at a given moment and make it available to the user at a later date, if necessary. Therefore, it is possible to assess the growth parameters of trees and the evolution of stands over time. The three-dimensional information it provides is also a great advantage in leaf area index estimates, especially in highly clumped stands (Huang and Pretzsch 2010). From an ecological point of view, using T-LiDAR should be a more convenient way to sample vegetation and to provide more sophisticated competition indexes.

Terrestrial LiDAR scanners are tools that provide very complete information about forest structure, especially if using several scans and high scanning resolutions. However, there are some disadvantages to using terrestrial LiDAR. Weather conditions must be considered carefully to obtain high quality point clouds (Dassot et al. 2011). Wind is the most problematic factor since it changes the tree value, especially in the upper part of the trees. The movement of the tree during a scan means that they are scanned at different positions, leading to the poor description of tree axes and foliage distribution and the increase of noise points (Dassot et al. 2011). The device must not be exposed to extreme temperatures while it is in operation (operating temperature generally between 0 and 40°C). In case of rain or snow, scanning can be carried out even if some raindrops are present on the mirror. Nevertheless, rain and snow are two factors that also reduce point cloud quality by intercepting numerous laser beams, leading to an increase of noise points as well. The deposition of snow on tree elements can lead to inaccurate estimation of wood diameters and volumes.

Lastly, using multiple scans increases measurement times, requires placing reference points in the field to merge scans, and adds processing steps. In a complex forest stand, scanning makes it necessary to use the lowest acquisition speed to improve signal-to-noise ratios and to avoid aberrant points, which leads to higher scanning times. Using high resolutions also increases data loading and processing times (Dassot et al. 2011). In the future, solutions should be found to easily deal with such quantities of data, especially in the case of standardised forest inventories using Terrestrial LiDAR. Terrestrial LiDAR scanners appear to be very suitable for commercial forest measurements, but additional research must be conducted to test and validate these instruments on dense and old-growth complex forests.

METHODS

SPECIES AND LOCATION

For this thesis, Red Pine (*Pinus resinosa)* was chosen as the ideal species for its good form, height and abundance in our specific plots. Trees measured in this study were located in several different Permanent Sample Plots (PSP) across northern Ontario (Figure 1). There were 15 trees sampled from several different areas across northern Ontario. The height and diameter measurements took place from November through to December.

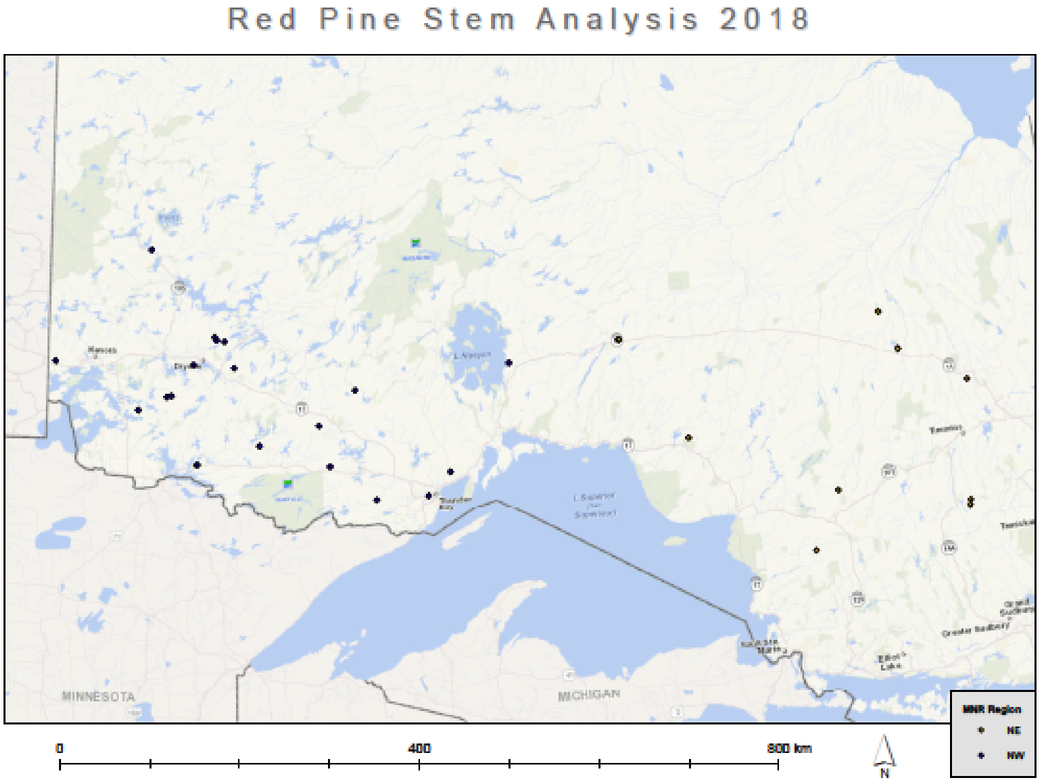

Figure 1. Location of Red Pine Stem Analysis Plots 2018 in Ontario, Canada.

FARO SCAN PROCEDURE

Figure 2. FARO Scanner in field

The MNR Growth and Yield department was involved in the scanning data collection using the FARO Focus (Figure 2). Trees measured for the study were flagged and measured for diameter at breast height (DBH). The FARO was set up in three locations, north, southeast and southwest. This is to ensure that every angle of the tree was scanned. Six targets were hung in the surrounding area to ensure the FARO was able to locate them. The targets are large white ornaments that are used by the scanner for reference points.

FELLING PROCEDURE

Once the scan had taken place, there was a pre felling procedure. The snow was first cleared from the base of the tree. Next, 1.3 meters from the base of the tree was measured and marked. The tree was also measured and marked at 10, 50, 90 centimeters to help with taper equation for basal area. The height to the first whorl, starting from 1.3 meters was determined. As well as the diameter of the dead branch. Then if possible, the height to dead crown was measured and subtracted from 1.3 if below that marker. The crew then felled the tree in a safely manner and proceed with the manual stem analysis procedure once on the forest floor (Figure 3). A tape measurer was stretched along the

Figure 3. MNR Growth and Yield Crew in Field

tree to the tip. A measurement was given for the total height of the tree and the height of the first live branch. Next, 1.3 was subtracted from the total height and a 10% sample from this number was calculated. This number would determine the distance between each measurement and wood cookie. A wood marker was used to draw a red line at each determined spot on the stem of the tree. Once marked, the diameter was taken at each increment. The tree was then cut into wood cookies at each increment all the way up the stem. This process was to ensure proper stem analysis in the lab. The cookies were labeled and taken back to lab for sanding and analysis.

STUDY DESIGN

This study was designed to ensure an appropriate number of samples were used to ensure quality analysis. In total, there were 15 trees sampled to make sure that there was a good representation of the population and limiting the influence of outliers. More samples would have been desirable but due to the amount of time available, 15 was the amount possible. The larger the sample size, the broader the range of possible data which forms a better picture for analysis.

We made sure that weather was relatively consistent to ensure proper scanning. We also made sure to consistently scan the same species for good quality data. The variables in this experiment are the volumes from the scan and stem analysis. Once scanned, we compared the stem analysis volume to the scan volume using a T-test to determine any variation in the data.

DATA ANALYSIS

3D Forest is an open-source software application that began in 2010 for LiDAR data segmentation, visualization and export of trees with parameters. The application 3D Forest was created to produce detailed information about forest stands and trees using terrestrial laser scanning technology and its result clouds of points. The application is released under the terms of the GNU General Public License v3 as published by the Free Software Foundation. The application is free for all users and is created by high quality team from Czech Republic, which makes this a prime software to use.

There is a very useful User Guide that explains how to use each aspect of the software. 3D Forest is capable of calculating the following tree attributes: position, DBH, Height, Cloud Length, Stem Curve, Convex Planar projection of the tree, concave planar projection of the tree and number of points. The software can also calculate many attributes of the crown, but for this thesis, crown was not analyzed.

The FARO produced its scans as .XYZ files, which is not compatible with the

3D Forest software. CloudCompare was used to transfer the .XYZ file format into a .LAS file format. To begin, each tree was opened by "creating a new project". This was to ensure each tree's measurements were organized in a specific folder. The project was labeled for example: "w01_2018_3dforest". There was no matrix assigned to the new project. Transformation matrix serve for reducing number of digits in coordinates values for faster data management (saving RAM) but was not necessary for this project.

Once the project was created, the tree was imported through "import basecloud". This is where the .LAS file is used and not the .XYZ file. After the tree was imported and able to see on the screen, the tree was adjusted for terrain. There are two automatic methods for doing so; terrain from octree and terrain from voxels. I determined through analysis that the voxel method is not able to differentiate between vegetation and terrain. Therefore, terrain from octree was chosen as the main method for terrain adjustment.

When conducting terrain adjustment, the input cloud is divided into cubes. Cubes which contain points and have the lowest z-value are considered as the "ground cubes". Terrain is then defined by the points in the ground cubes. The output will be two values: w01_terrain and w01_vegetation (Figure 4).

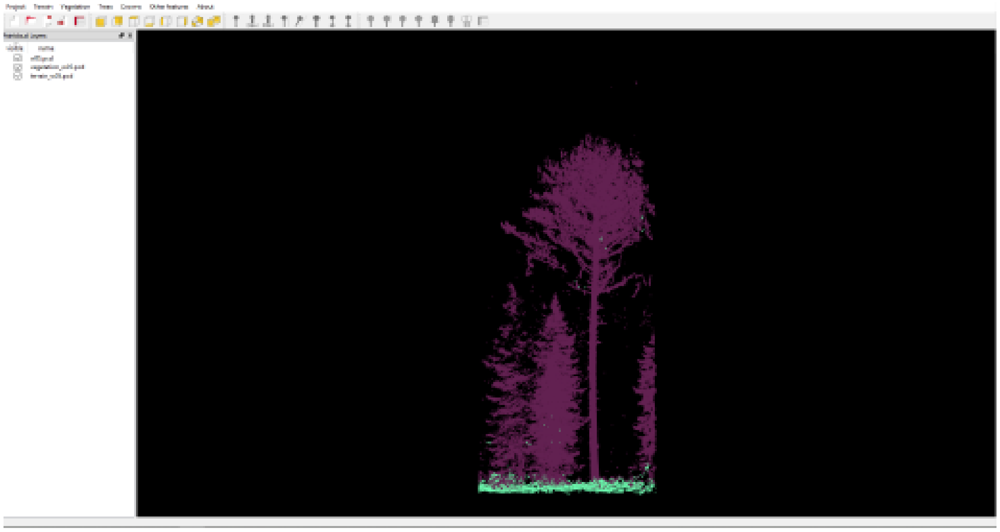

Figure 4. Terrain Adjustment output values and visual display.

Once the terrain is adjusted, automatic vegetation segmentation was conducted. This creates a colourful display of each tree in the scanned point cloud (Figure 5). The automatic approach is based on distance between points and minimal number of points forming clusters and an angle between centroids of the clusters. Automatic segmentation is completed by dividing the entire vegetation into horizontal slices with user-defined input size [cm]. Within these slices, clusters of points are detected and reconstructed into bases of each tree. The rest of the tree is formed by identifying other clusters within a certain distance of each other with segments the different trees apart from each other.

In some scenarios, the automatic segmentation is not fully correct, and the main Red Pine tree could be split into two segments. This is seen in Figure 5 below. In order to fix this, "cloud merge" must be used to link the two parts of the tree together.

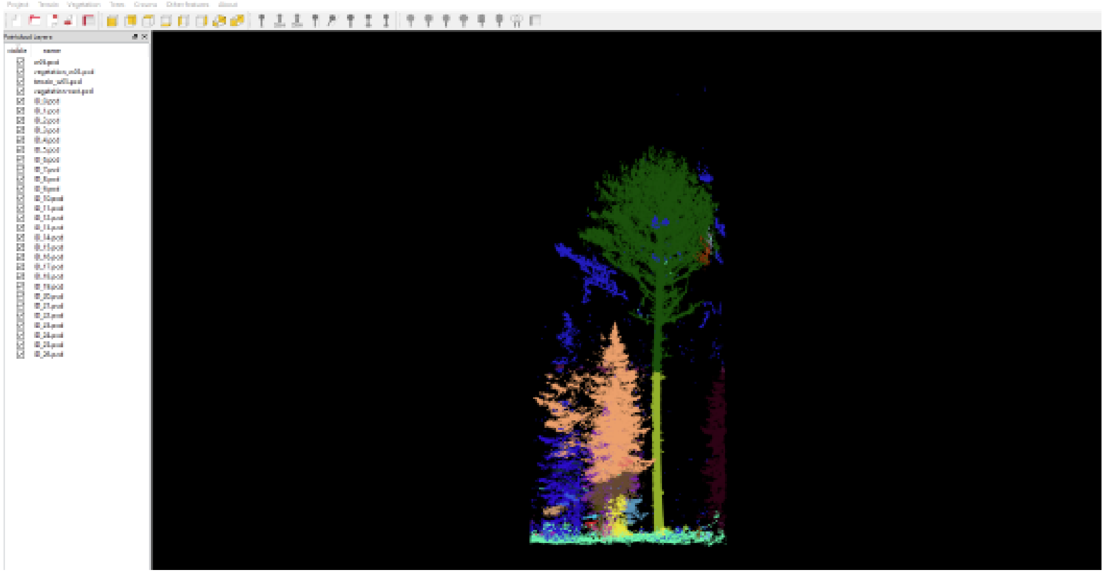

Figure 5. Automatic Vegetation Segmentation Output.

Before conducting analysis on the single tree, you must position the tree cloud. Tree base position is a key parameter providing a baseline for computation of other tree parameters such as DBH, tree height and stem curve and affects also the visualization of convex/concave tree projection. Therefore, none of these functions are available until the tree position is calculated. There are two methods to conducting tree positioning and actual tree position may slightly vary according to the computation method used. I determined through analysis the both methods; “position by lowest point and “position RHT” produced the exact same results. Therefore, position by lowest point was consistently used.

Once the lowest point is determined, the rest of the functions will be available to calculate tree parameters. The first parameter determined was DBH. The diameter at breast height (DBH) is computed from the subset of points of the tree cloud, which lie between 1.25 and 1.35 m above the tree base position (so called DBH cloud). There are two methods of DBH estimation implemented in 3D Forest: i) randomized Hough transformation (RHT) and ii) least square regression (LSR). Both use the same DBH cloud, but there may be considerable differences between the results. RHT usually gives better results, because the LSR function frequently overestimates the diameter value in the presence of outlying points. The usual reason of the big difference between both methods is that the subset of points from which DBH is calculated includes overhanging branches or points which do not belong to tree point cloud (i.e. the tree was not segmented appropriately). This may be fixed by the Tree cloud edit function.

For DBH RHT, the DBH subset of the tree cloud (i.e. from 1.25 to 1.35 m) is projected to a horizontal plain (Z coordinates are transformed to 1.3m). Then, for each point the method searches every possible center of the circle. The most frequent circle center is then selected as a resulting center (Figure 6).

The DBH LSR method projects the points lying between 1.25 and 1.35 m to a horizontal plain (Z coordinates are transformed to 1.3m). Then the circle is fitted to these points by the Least squares' regression. The method is based on minimizing mean square distance between fitted circle and data points, for circle fitting Gauss-Newton method is used.

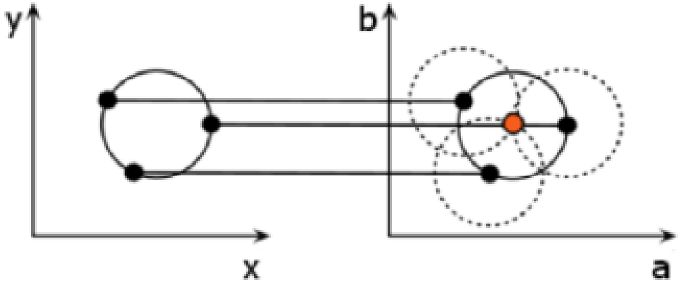

Figure 6. DBH RHT: Searching center of circle with known parameter

The height and length parameters were then calculated using the automatic algorithm. After, the stem curve was determined in 1 m intervals (Figure 7). Using the

Figure 7. Stem curve output on red pine tree.

stem curve application. The stem diameters are computed as circles by Randomized Hough transformation from 7 cm high slices of the tree cloud. They are displayed as 7 cm high cylinders defined by the RHT fitted circles; the number of RHT iterations may be set by the user. The algorithm starts with computing first the stem diameter at 0.65 m above the ground, then at 1.3m and 2m above the ground and then continues computing diameters with 1 m spacing until the new diameter is two times wider than both previous two diameters.

For some trees, editing of the tree cloud was needed in order to reduce noise from other points and trees seen. Also, for each tree, in order to see the differences in results, the branches were edited away from the stem using the same function. In order to do so, the edit application was used to remove those points and saved as a new tree cloud. Once all tree parameters were determined (DBH (RHT and LSR) Height, Length and Stem Curve) the data was exported. To export dbh, height and length, "export all tree attributes" was used. To export stem curve, "export stem curve" was used. These were saved as excel files into the specific tree's folder.

VOLUME CALCULATIONS

Volume for each tree was determined using Honers standard volume equation for total volume of the tree (Vt). Honers was picked because the merchantable volume is not able to be calculated without the bark thickness, which LiDAR cannot determine. For Honers volume equation the variables needed were: DBH, height and the co-efficients for red pine found in Honers tables (Appendix 1):

A = 161.764

B = 24696.1

The Honers standard volume equation for total volume:

$$Vt(dm^3) = \frac{Dbhob^2}{A + \frac{B}{Ht}} * 1000$$

A new version of 3D Forest that calculates Quantitative Structure Models (QSM) was used to calculate the volume of the scanned trees as a comparison. QSM uses cylinders to define the geometry and topology of the tree. The cylinders are then used to calculate the outside volume of the tree using an algorithm in the software.

STATISTICAL ANALYSIS

T-Test

Using excel, 7 statistical t-test analysis were done on these values: DBH RHT vs. Manual; DBH LSR vs. Manual; Height vs. Manual; Volume DBH RHT vs. Manual; Volume DBH LSR vs. Manual; Volume DBH RHT with Edits vs. Manual and Volume DBH LSR with Edits vs. Manual

RESULTS

Due to poor scanning in the field, only 13 trees were able to be processed in the software.

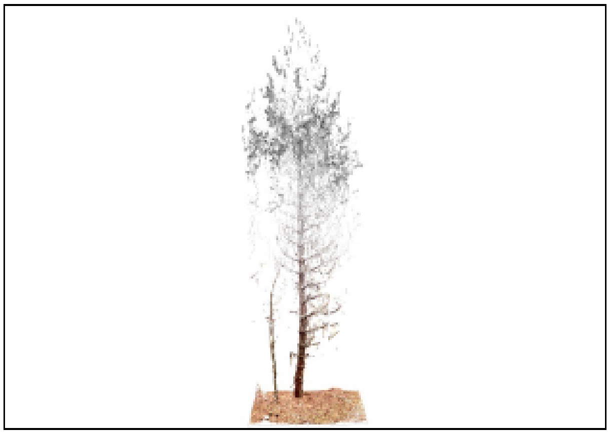

Figure 8. Scan of Red Pine with colour assigned. (Source: MNR Field Scan 2018)

HEIGHT

The LiDAR scan output results were accurate when compared the manual field measurements (Table 1). The largest difference between a LiDAR height and Manual height was 2.04 meters and the lowest difference was 0.01 meters. The average difference between the two was 0.56 meters. A visual comparison between the two results can be seen in Figure 9.

A T-test was executed to statistically analyze the LiDAR scan height and the manual field measured height. The P-value received was 0.90 (Table 2). These results show that there is no significant difference between the two variables and that the FARO is able to accurately produce Red Pine tree heights.

Table 1. Heights of trees from LiDAR and manual measurements

Plot-Tree	LiDAR Height	Manual Height
W02-45	20.57	20.48
W03-03	16.63	16.61
W04-74	16.67	15.87
W05-05	22.22	22.81
W06-48	22.98	23.62
W07-27	23.62	24.4
W08-38	17.92	17.6
W09-03	25.24	25.6
W11-11	15.33	16.39
W12-75	21.07	21.12
W13-28	20.7	18.66
W16-61	26.82	26.25
W17-02	23.94	23.95

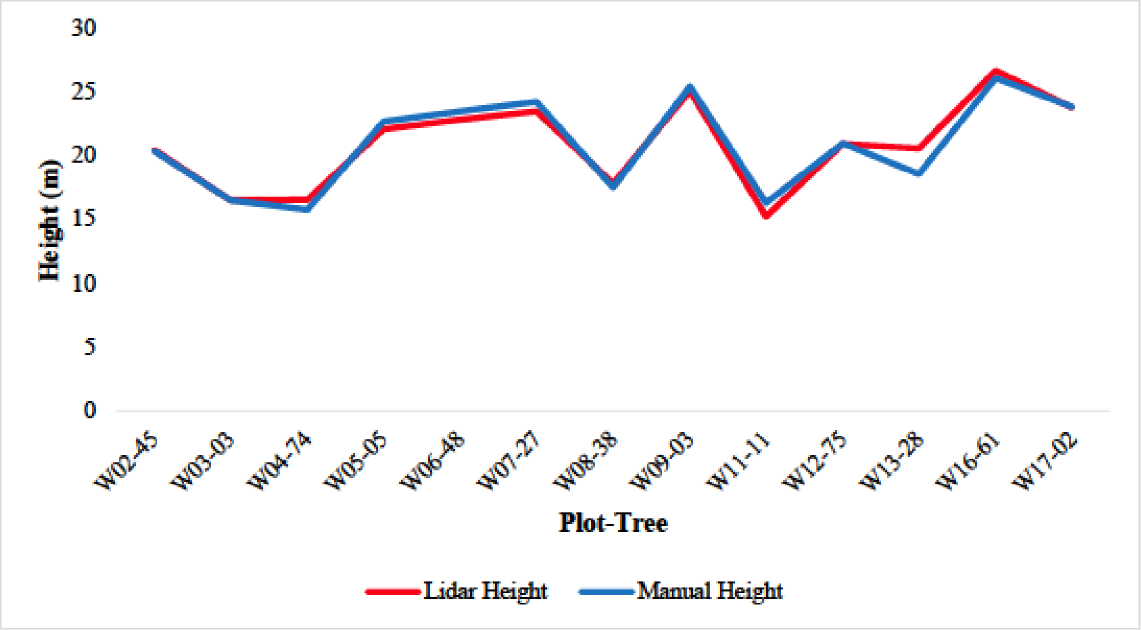

Figure 9. Comparison of LiDAR Height and Manual Height results.

Table 2. T-test Results for Height Manual vs. LiDAR

	LiDAR	*Manual*
Mean	21.05462	21.02769
Variance	12.70741	13.60642
Observations	13	13
Pearson Correlation	0.97571	
Hypothesized Mean Difference	0	
df	12	
t Stat	0.120021	
P(T<=t) one-tail	0.453226	
t Critical one-tail	1.782288	
P(T<=t) two-tail	0.906453	
t Critical two-tail	2.178813	

DIAMETER AT BREAST HEIGHT (DBH)

As explained in the methods, there are two forms of DBH; DBH RHT and DBH LSR. Both these methods were analyzed since each gave individual results. Each tree was also edited to remove all branches and noise from the surrounding point cloud, these results are under “EDIT RHT” and “EDIT LSR”. Table 3 below shows an overall view of each DBH calculated for each tree. It is important to notice the large differences between many non-edited LSR values versus the edited LSR values (Figure 10).

A statistical T-test was run on each DBH (edited and non-edited) against the Manual field measurement DBH (Table 4). There was significance found between the DBH LSR and the Manual field measurements of DBH. This means that the Automatic DBH LSR with no edits is not accurate for Red Pine compared to the manual measurements of a human ground surveyor. This is due to the many outliers in the DBH LSR values such as tree W07-27 with a DBH of 141.02 cm and tree W12-75 with a DBH of 143.71 cm (Table 3). These values are impossible for Red Pine trees in North America. Another notable point is that the Edited DBH LSR values had the best results for the T-test with a P-Value of 0.887 (Table 4). Runner up is the Non-edited DBH RHT with a P-Value of 0.825 (Table 4).

Table 3. DBH results from both LiDAR and manual measurements.

Plot-Tree	DBH RHT	DBH LSR	EDIT RHT	EDIT LSR	DBH Manual
W02-45	22.6	22.47	22.6	22.47	25
W03-03	21.6	82.83	21.4	23.55	28.1
W04-74	19.4	111.03	20.4	18.82	22.6
W05-05	33.6	37.59	34.2	37.57	37.8
W06-48	16.6	19.55	16.6	19.55	28.4
W07-27	29.2	141.02	27.2	29.88	33.7
W08-38	15.4	15.42	15.4	15.42	20.9
W09-03	38.6	39.03	38.6	39.03	30.5
W11-11	86.4	89.55	30.2	45.34	19.7
W12-75	18	143.71	20.6	23.52	25.3
W13-28	27.4	27.64	27.4	36.04	27.5
W16-61	43.8	49.90	49.2	48.75	48.2
W17-02	22.4	23.41	22.4	23.41	30.8

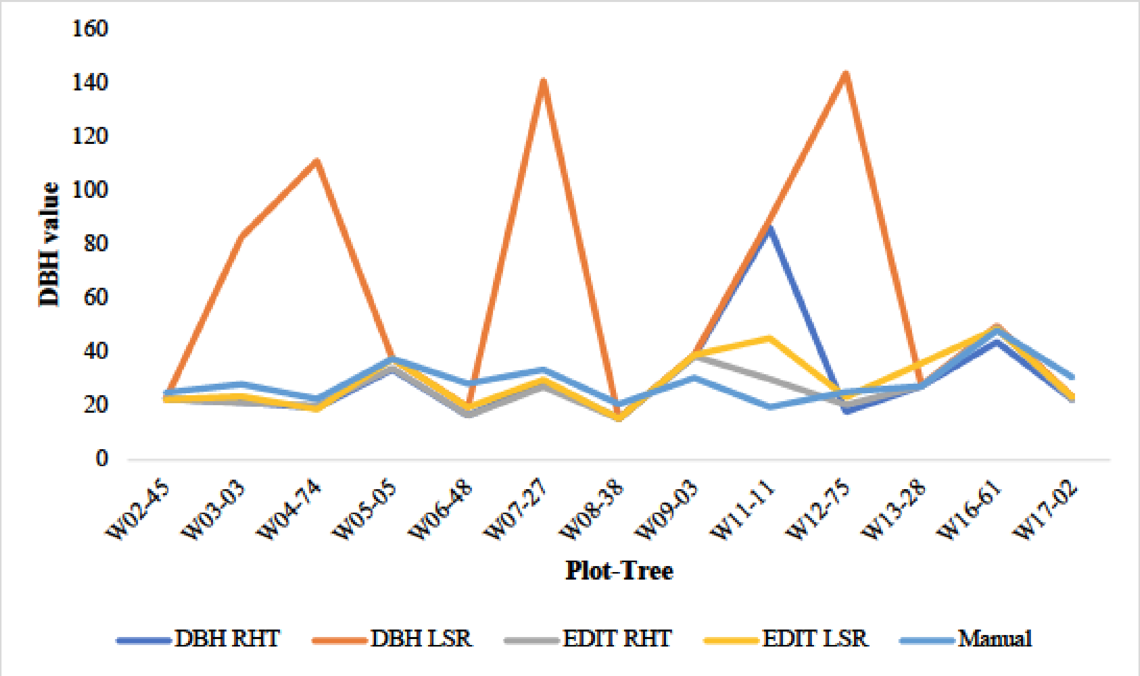

Figure 10. Comparison of each LiDAR DBH value and Manual values.

Table 4. T-test results from each LiDAR DBH Value compared to Manual DBH measurement.

	P-Value
DBH RHT	0.825
DBH LSR	0.030
EDIT DBH RHT	0.178
EDIT DBH LSR	0.887

Source. Appendix

VOLUME

The volume of Red Pine was calculated using Honers equation for total volume. Each DBH was used for a new volume calculation in order to compare results. The manual volume was calculated using the height and DBH measured in the field by the MNR growth and field crew. Included in Table 5 is the DBH RHT and LSR "Edit Surroundings" and "Edit out Branches". "Edit surroundings" was used when there was another bush or part of tree that was not meant to be in that point cloud and was therefore skewing results. This was not needed for every tree, nor was used for statistical analysis, because not every Red Pine had noise in the terrain. Though it is important to note that editing out extra noise greatly improved the volume from the original automatic 3D forest values. For example, tree W03-03 had a DBH LSR volume of 4166.56 dm3, and when the surroundings were edited the volume for DBH LSR was now 340.34 dm3, a much more realistic number (Table 5). "Edit out branches" was used for every tree because each Red Pine had a crown that was able to be removed through 3D Forest.

Statistical T-test results were calculated for comparison between "automatic 3D Forest" DBH RHT AND LSR and "Edit out Branches" DBH RHT and LSR (4 t-tests in total) (Table 6). DBH RHT volume had a very large outlier for tree W11-11 with a volume of 4211 dm3, which is too high for a tree with a height of 16 m and a DBH of 20 cm (Figure 11). Despite some outliers, the T-test results had a P-value of 0.625 which means there is no difference between the LiDAR and Manual Volume (Table 6).

The DBH LSR volume had a T-test p-value of 0.047, which means the results are significant and there is a difference between the LiDAR volumes and the Manual Volumes (Table 6). This is evident when looking at multiple outliers for DBH LSR volumes compared to the Manual volumes (tree W03, W04, W07, W11, and W12) (Figure 12).

The Edited DBH RHT had a t-test p-value of 0.232 (Table 6). These results had no major outliers like the previous volumes but instead, each volume was not accurate compared to actual volume of the tree (Figure 13). This can be understood when averaging all the volumes. Edited DBH RHT gives an average volume of 619.5 dm3 for all trees, while the manual volume has an average of 711.3 dm3. For most of the Edited DBH RHT volumes, they were underestimated compared to the manual volumes. The closest volume was for tree W13-28 which was off by 45.2 dm3.

Edit DBH LSR had a t-test p-value of 0.766 (Table 6). This is the largest p-value which means this form of DBH produced the most accurate volume for Red Pine. Which means, before editing DBH LSR gives the least accurate volumes, but after editing out branches, DBH LSR gives the most accurate volumes. Edit DBH LSR gives an average volume of 742.8 dm3 for all trees, while the manual volume has an average of 711.3 dm3. Similar to the Edit DBH RHT, most of the volumes were underestimated compared to the manual volumes (Figure 14). The Edit DBH RHT and LSR had the exact same 4 trees that were overestimated in volumes (W09, W11, W13, W16) (Table 5).

Table 5. Calculated Red Pine Volume values for each LiDAR DBH (edit and non-edit) and manual measurement.

Plot-Tree	Volume (dm3)						
	3D Forest		Edit Surroundings		Edit Out Branches		Manual
	DBH RHT	DBH LSR	DBH RHT	DBH LSR	DBH RHT	DBH LSR	
W02-45	374.91	370.68			374.91	370.68	457
W03-03	283.31	4166.56	310.32	340.34	277.34	335.92	478.96
W04-74	229.04	7501.81	178.42	229.57	197.29	167.88	297.31
W05-05	886.71	1109.69			918.66	1108.86	1148.17
W06-48	222.87	309.18			222.87	309.18	668.06
W07-27	706.22	16472.63	613.24	739.84	609.42	735.23	967.45
W08-38	154.01	154.41			154.01	154.41	279.12
W09-03	1306.74	1335.74			1306.74	1335.74	825.82
W11-11	4211	4523.65	772.71	838.98	514.79	1160.22	232.59
W12-75	242.9	15484.16	318.14	414.73	318.14	414.73	480.88
W13-28	554.14	564.06			554.38	959.34	509.18
W16-61	1772.11	2299.9			2185.46	2145.66	2107.12
W17-02	420.46	459.08			420.46	459.08	795.23

Table 6. T-test results for each volume using different LiDAR DBH for edit and non-edit (height constant) compared to manual volume.

	P-Value
DBH RHT	0.625
DBH LSR	0.047
EDIT DBH RHT	0.232
EDIT DBH LSR	0.766

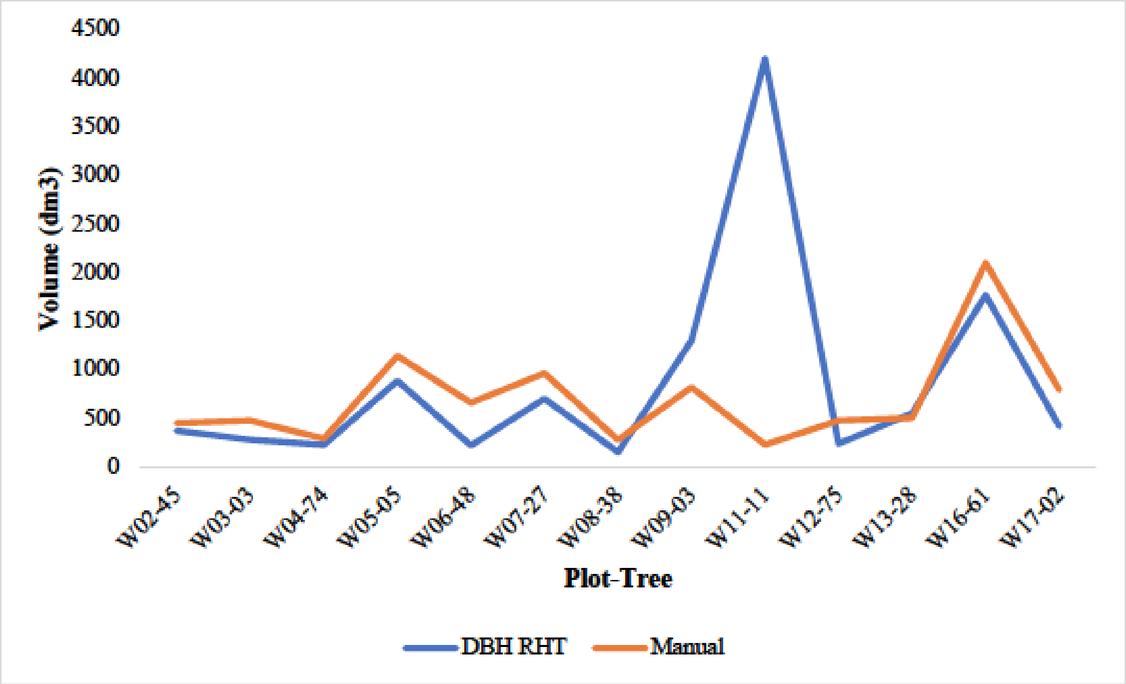

Figure 11. Comparison between volumes for LiDAR DBH RHT and volume for manual

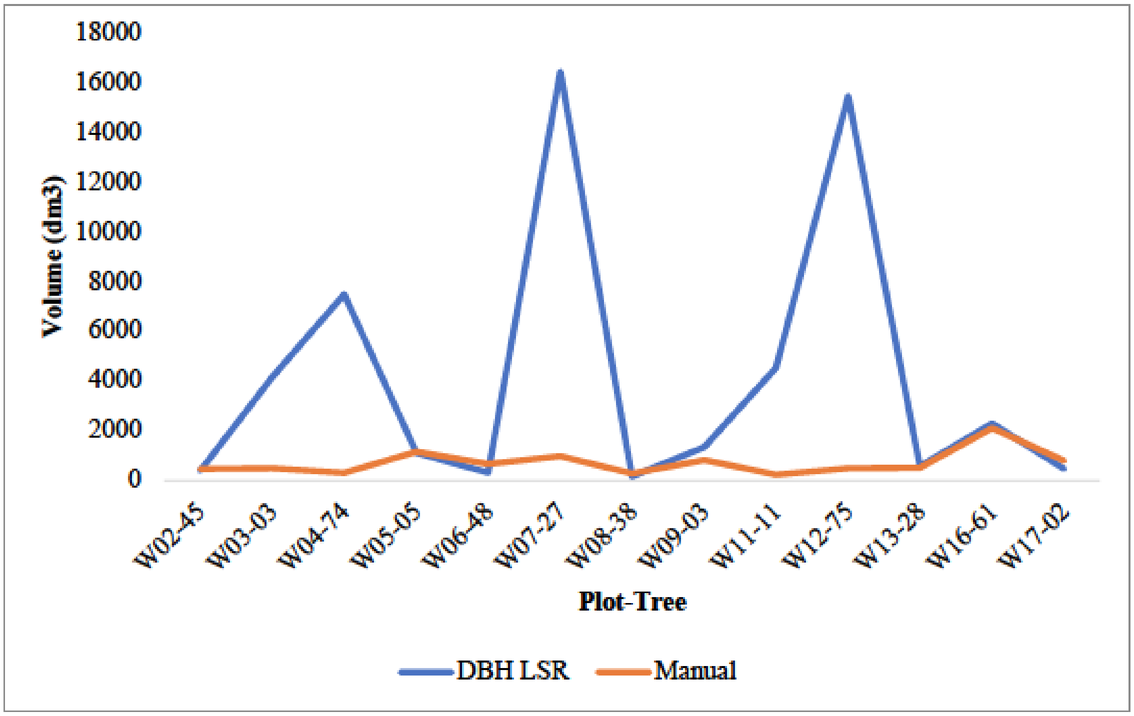

Figure 12. Comparison between volumes for LiDAR DBH LSR and volume for manual

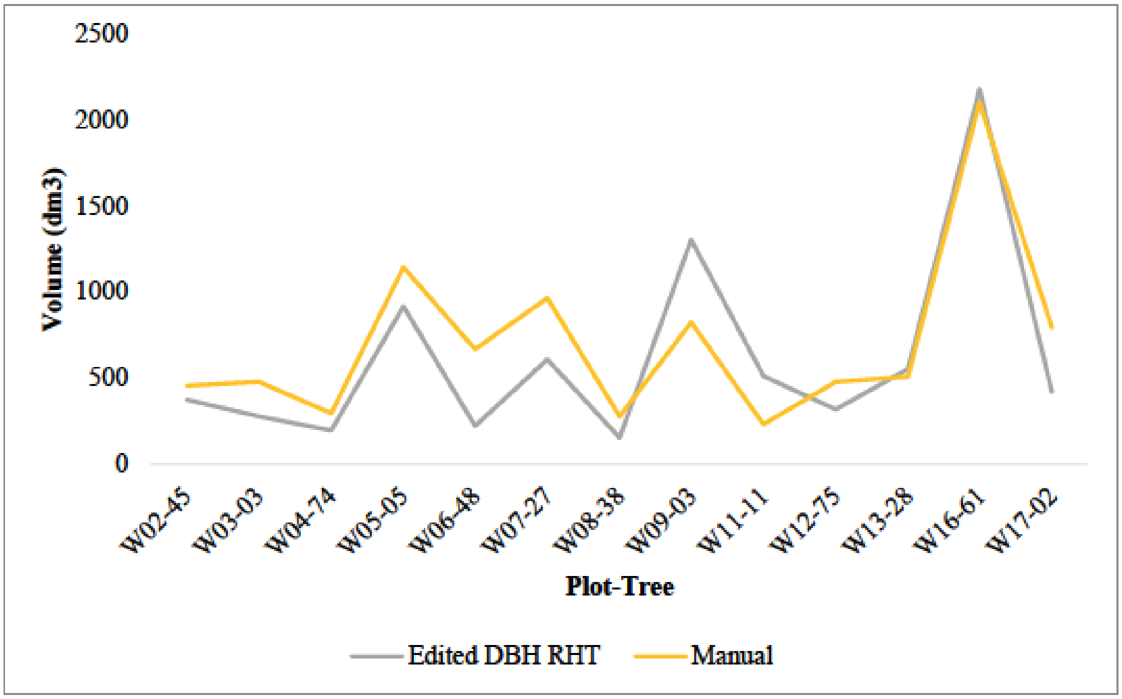

Figure 13. Comparison between volumes for Edited LiDAR DBH RHT and volume for manual

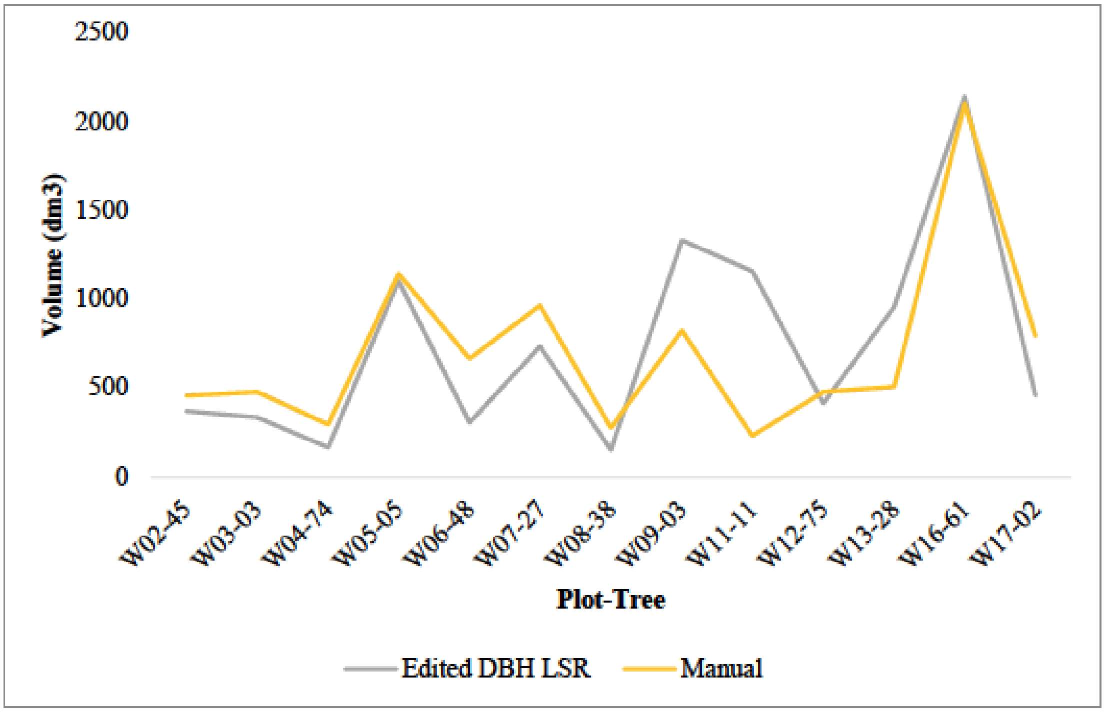

Figure 14. Comparison between volumes for Edited LiDAR DBH LSR and volume for manual

STEM CURVE

Stem curve was calculated using 3D Forest and manual results were also provided by the MNR Field crew. The problem with the stem curve that 3D forest produced was that the increments did not follow the form of a tree. In Figure 15, the bottom line represents the natural flow of stem curve, going from larger numbers to smaller numbers. The top line shows what the 3D Forest software produced, which shows a very crooked, unrealistic and disproportionate tree. For this reason, stem taper was not able to be calculated and was disregarded for these results. Better algorithms will be needed in order to record stem taper from the point cloud in the future.

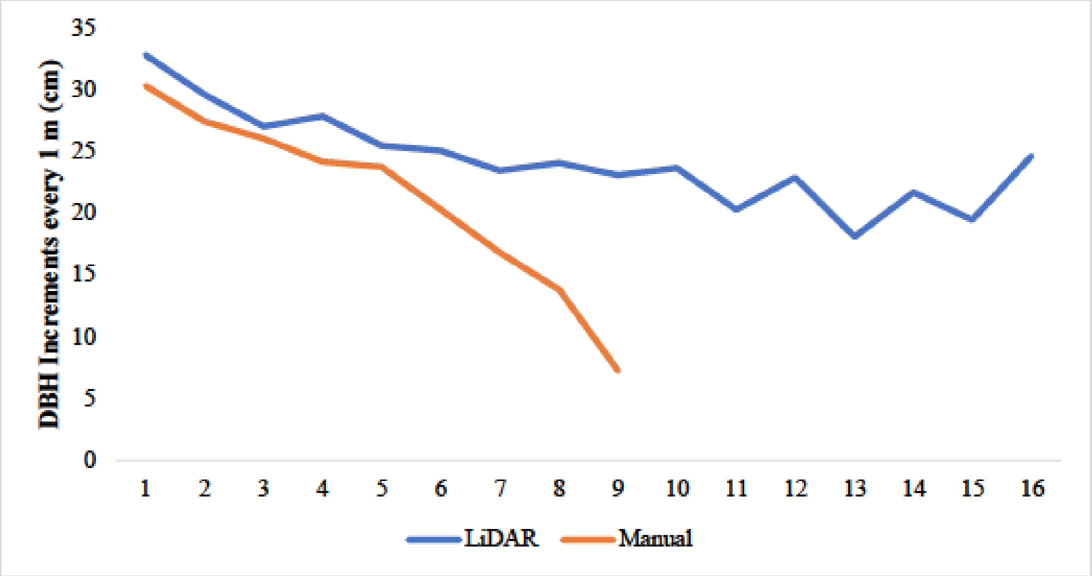

Figure 15. Stem curve of both LiDAR and Manual increments every 1m up the tree.

VOLUME QSM

Volume using Quantitative Structure Models (QSM) was an extra comparison to see if the 3D Forest software was able to compute similar volumes. QSM volumes were calculated with DBH LSR since it was shown to be the most accurate. Three trees were not able to be calculated using QSM due to the amount of time the software was taking to compute the calculations (Table 7). For trees W02 and W17, over 20 minutes was spent waiting with no results given. Waiting this amount of time is not beneficial when results can be computed quicker manually. Tree W08 was calculating but would not omit any values for volume, just 0.000. The results show that for some trees (W03, W06, W07, W11) QSM results are similar or closer to the manual volumes compared to the "Edit out Branches" volumes (Table 7). For other trees (W04, W05, W09, W12, W13, W16), QSM volume values are far off from the manual volume values (Table 7).

Table 7. QSM volume calculation comparison.

Plot-Tree	Volume (dm3)					
	3D Forest		QSM	Edit Out Branches		Manual
	DBH RHT	DBH LSR	DBH LSR	DBH RHT	DBH LSR	
W02-45	374.91	370.68	N/A	374.91	370.68	457
W03-03	283.31	4166.56	333	277.34	335.92	478.96
W04-74	229.04	7501.81	173	197.29	167.88	297.31
W05-05	886.71	1109.69	1292	918.66	1108.86	1148.17
W06-48	222.87	309.18	435	222.87	309.18	668.06
W07-27	706.22	16472.63	974	609.42	735.23	967.45
W08-38	154.01	154.41	N/A	154.01	154.41	279.12
W09-03	1306.74	1335.74	224	1306.74	1335.74	825.82
W11-11	4211	4523.65	327	514.79	1160.22	232.59
W12-75	242.9	15484.16	597	318.14	414.73	480.88
W13-28	554.14	564.06	815	554.38	959.34	509.18
W16-61	1772.11	2299.9	2312	2185.46	2145.66	2107.12
W17-02	420.46	459.08	N/A	420.46	459.08	795.23

SCAN TIMES

Scan times were recorded for each tree and location (Table 8). The average scan time was 37 minutes to complete.

Table 8. Red Pine Scan times from MNR Growth and Yield Crew.

Plot Name	Date	Tree #	Start Time (Hrs - EST)				District
			1	2	3	4	
W01-2018	2018-10-30	51	N/A	N/A	N/A	N/A	Thunder Bay
W02-2018	2018-11-01	45	N/A	N/A	N/A	N/A	Thunder Bay
W08-2018	2018-11-06	38	12:00	12:12	12:25	12:38	Kenora
W09-2018	2018-11-07	3	11:28	11:37	11:48	11:57	Kenora
W15-2018	2018-11-09	34	13:18	13:28	13:38	13:48	Kenora
W13-2018	2018-11-10	28	15:41	15:54	16:03	16:14	Kenora
W16-2018	2018-11-12	61	13:48	13:59	14:11	14:22	Rainy River
W03-2018	2018-11-13	3	10:33	11:42	11:53	12:06	Rainy River
W07-2018	2018-11-20	27	N/A	N/A	N/A	N/A	Dryden
W05-2018	2018-11-22	5	11:23	11:36	11:51	12:10	Dryden
W04-2018	2018-11-23	74	15:39	15:54	16:06	16:21	Red Lake
W12-2018	2018-11-25	75	10:54	11:19	11:33	11:45	Sioux Lookout

LIDAR PROCESSING

The LiDAR processing results were recorded to show the procedure and keep track of problems with each tree (Table 9). For example, tree W09 took a very long time to align due to target distribution being less than optimal.

Table 9. LiDAR Processing process and notes

Plot	Scan Numbers	Aligned in Scene	Scans Colourized	Point Cloud Created	Tree Isolated	.xyz exported	Notes
W02-48	005-009	Yes	Yes	Yes	Yes	Yes	
W03-03	039-042	Yes	Yes	Yes	Yes	Yes	Initial run with no colour. . Colourized shows lots of haze.
W04-74	027-030	Yes	Yes	Yes	Yes	Yes	
W05-05	022-025	Yes	Yes	Yes	Yes	Yes	
W06-48	039-042	Yes	Yes	Yes	Yes	Yes	
W07-27	018-021	Yes	Yes	Yes	Yes	Yes	
W08-38	010-013	Yes	Yes	Yes	Yes	Yes	
W09-03	014-017	Yes	Yes	Yes	Yes	Yes	2+ hours to align. Target distribution not optimal. Too many targets on the ground. Crew members in scans. Caused significant alignment challenges. Glare issues in colourized cloud
W11-11	035-038	Yes	Yes	Yes	Yes	Yes	
W12-75	031-034	Yes	Yes	No	No	No	Terrible registration…need to rerun
W13-28	022-025	Yes	Yes	Yes	Yes	Yes	
W16-61	026-027,037-038	Yes	Yes	Yes	No	No	Took many manual points to tie together. Issues caused by poor target placement. Target tree looks split…need to address this
W17-02	043-046	Yes	Yes	Yes	Yes	Yes	

DISCUSSION

COMPARISON OF TREE HEIGHTS

Tree heights obtained from the FARO terrestrial LiDAR scanner were estimated as the maximum (highest) laser pulse return within the crown radius footprint. These were then compared with the field measurements of individual tree heights. The terrestrial LiDAR measurements were shown to be very accurate compared to the manual measurements. These results show that the FARO is accurate in determining height of Red Pine. More research will need to be done on different species to broaden these results.

Magnussen and Boudewyn (1998) and Maltamo et al. (2004) found discrepancies between airborne LiDAR estimated tree heights and those measured in the field. Therefore, terrestrial LiDAR could be proven to be more accurate than airborne LiDAR. Although, studies from Hopkinson (2004) and Chasmer (2006), found that heights of individual red pine trees are typically underestimated using terrestrial LiDAR sensors due to reduced numbers of laser pulse returns within the upper canopy because of shadowing by branches and stems near the ground surface. My research study shows that the terrestrial LiDAR technology is constantly becoming more advanced and accurate in their measurements. In 13 years, my results now display that the Terrestrial LiDAR scanner is very accurate in producing tree heights.

This study was done on single trees and will be important for the future, because tree heights could be applied to a whole stand. Currently, it takes too long to take the tree heights of an entire stand, so a sample is taken. With these results, it could be tested on a whole tree stand to get a more accurate measurement of the entire stands tree heights.

COMPARISON OF DIAMETER BREAST HEIGHT (DBH)

Tree DBH obtained from the FARO scanner were calculated using 3D Forest software by fitting cylinders around the tree point cloud. Two methods were used to determine DBH, LSR and RHT. These results were then compared to the manual field measurements. Results showed that before editing the tree point cloud, RHT was more accurate than LSR compared to manual field measurements. After editing the tree point cloud, LSR was determined to be more accurate.

DBH RHT is determined by projecting the subset of the tree cloud onto a horizontal plain (Z coordinates are transformed to 1.3m). Then, for each point the method searches every possible center of the circle. The most frequent circle center is then selected as a resulting center. Therefore, an un-edited version of the point cloud with, branches still attached, is accurate but not as accurate as DBH LSR after editing.

The DBH LSR method projects the points lying between 1.25 and 1.35 m to a horizontal plain (Z coordinates are transformed to 1.3m). Then the circle is fitted to these points by the Least squares' regression. The method is based on minimizing mean square distance between fitted circle and data points, for circle fitting Gauss-Newton method is used. DBH LSR is therefore better suited for an editing tree with branches removed to limit noise when fitting the circle using least squares regression. The only downside with this method is the need for editing the branches. It adds on average, roughly 10 minutes per tree. Therefore, these results show that if you would like to have a slightly more accurate DBH but more time editing the edited LSR DBH would be better. But if you would like an accurate DBH with less editing time, DBH RHT would be the best choice.

The reason for the DBH to be inaccurate in the point cloud is due to reference points when scanning. In order for the FARO to be accurate, reference points must be properly placed in the forest for the scanner to see. These reference points are 6 white orbs that are hung from branches. If the orbs are hung too low or a slope is not taken into consideration, then the scanner will not be able to see it and have no frame of reference for the point cloud. For some of the scans, the crew set up the reference points too poorly that they were unable to be seen. In this case, manual tie points were needed to put into the software. On slopped areas, the target tree was not visible. Better training would be able to solve this issue for future studies.

When considering accuracy, it is important to take a step away from the T-test results and look at the numbers to see which trees would be classified in the wrong DBH Class (greater than 2cm off). When looking at the results in this way, for DBH LSR (the best P-Value), trees W02, W03, W04, W06, W07, W08, W09, W11, W13, and W17 would all be called into the wrong DBH Class. That is 10 out of 13 trees being the wrong DBH, which is a big error and would greatly affect the determination the future of the stand and the volumes. Therefore, I would say that the FARO was statistically accurate when determining DBH, but not accurate when considering the forestry point of view. More research will need to be done for different species and higher sample sizes for better determination of the accuracy of terrestrial LiDAR for DBH.

COMPARISON OF VOLUMES

Tree Volumes were obtained using the different sets of DBH's (LSR and RHT) and height for both LiDAR and Manual Field measurements. Due to the DBH values being slightly off, it was assumed that the volumes were also going to be slightly off as well. Without editing the tree, the volumes using DBH LSR had statistically significant difference. After removing the branches of the trees point cloud, the volumes using DBH LSR gave the best results statistically. Although when looking at the results, there are significant differences and a few outliers that greatly skew the results. These results show that terrestrial LiDAR is statistically capable of producing volumes of Red Pine, but if this were to be applied at stand level instead of individual tree level, total volumes not be accurate which could jeopardize future stand projections and volumes for the mill.

The problem with this study was the outliers. There were 4 trees that were consistently overestimated (W09, W11, W13, W16). The Edit DBH RHT and LSR had the exact same 4 trees that were overestimated in volumes and DBH. In future studies, a bigger sample size should be used, and outliers could be removed in order to focus in on the accuracy of the machine. These 4 trees most likely had something wrong with the scan, such as target points. Therefore, in the future, better training will be needed for crew members that are using the FARO machine to execute best results.

TERRESTRIAL LIDAR APPLICATIONS AND FUTURE USES

After analyzing the results, it was determined that terrestrial LiDAR is statistically accurate at determining heights, DBH LSR when edited, DBH RHT and volume using DBH RHT and DBH LSR when edited. Editing all branches off the stem of the point cloud was determined as the best form of terrestrial LiDAR analysis while using DBH LSR from the edit. Although, this has implications due to the amount of time that it takes to remove the branches compared to the amount of time it takes to measure the tree in the field. When branch removal is needed using 3D Forest software, it would be quicker to have measured the DBH in the field.

The future of 3D Forest software will be QSM calculations. A newer version of 3D Forest that utilized QSM measurements was used to determine volume in the software, instead of manual calculations, which would save time. Although the measurements were determined to be more inaccurate than manual calculations of models at this time. This software is very early in its use. In the future, this software will be more developed and should be tested again, with a larger sample size and different species.

CONCLUSION

This study demonstrated that terrestrial LiDAR can be very useful for forest inventory in the right environments and with proper training. Correct use of the FARO and the reference points must be undertaken in order to receive quality results. Stands with less density will produce better scans due to less noise. Overall, the FARO was very accurate in calculating tree heights and this should be applied to future studies with other species and a bigger sample size. In general, the entire study should be done with other species to determine a broader range of uses for the Terrestrial LiDAR.

Volume using DBH LSR with editing of the tree stem resulted in the best comparison to the manual field measurements. Although this can be time consuming. The average scan took 32 minutes, add on roughly 30 minutes of computer analysis and single trees would take roughly an hour. More research should be done on entire stand scanning times.

This study is very important for the future of forest inventory with the advancement of technology and the need for fast and accurate data. As well as to update the current Growth and yield data collection methods. Current FRI data is not appropriate for the use in determining species composition and volume. Having accurate data that can be used again and is quicker to collect, will benefit industries by saving time and money. Terrestrial LiDAR will constantly be improving in machines and software in the future. Therefore it is important to keep testing, training and teaching about the uses of LiDAR. The FARO is already being used in many other industries, and with consistent improvement and adjustment of the software, the FARO could be capable of producing accurate and quality forest stand data.

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APPENDIX 1

Honers Total Volume for Red Pine
(dm^3) - stump and top included

Dbhob class (2cm)					Total height Class (m)						
	6	8	10	12	14	16	18	20	22	24	26
8	15.0	19.7	24.3	28.8	33.2	37.5	41.7	45.8	49.8	53.7	57.6
10	23.4	30.8	38.0	45.0	51.9	58.6	65.2	71.6	77.9	84.0	90.0
12	33.7	44.3	54.7	64.9	74.8	84.4	93.9	103.1	112.1	120.9	129.5
14	45.8	60.3	74.5	88.3	101.8	114.9	127.8	140.3	152.6	164.6	176.3
16	59.8	78.8	97.3	115.3	132.9	150.1	166.9	183.3	199.3	215.0	230.3
18	75.7	99.7	123.1	146.0	168.2	190.0	211.2	232.0	252.3	272.1	291.5
20	93.5	123.1	152.0	180.2	207.7	234.6	260.8	286.4	311.5	335.9	359.8
22	113.1	149.0	183.9	218.0	251.3	283.8	315.6	346.6	376.9	406.5	435.4
24	134.6	177.3	218.9	259.5	299.1	337.8	375.5	412.4	448.5	483.7	518.2
26	158.0	208.1	256.9	304.5	351.0	396.4	440.7	484.0	526.4	567.7	608.1
28	183.3	241.3	297.9	353.2	407.1	459.8	511.2	561.4	610.4	658.4	705.3
30	210.4	277.0	342.0	405.4	467.3	527.8	586.8	644.4	700.8	755.8	809.6
32	239.4	315.2	389.2	461.3	531.7	600.5	667.6	733.2	797.3	859.9	921.2
34	270.2	355.8	439.3	520.8	600.3	677.9	753.7	827.7	900.1	970.8	1039.9
36	303.0	398.9	492.5	583.8	673.0	760.0	845.0	928.0	1009.1	1088.4	1165.9
38	337.6	444.5	548.8	650.5	749.8	846.8	941.5	1034.0	1124.3	1212.7	1299.0
40	374.0	492.5	608.0	720.8	830.8	938.3	1043.2	1145.7	1245.8	1343.7	1439.3
42	412.4	543.0	670.4	794.7	916.0	1034.4	1150.1	1263.1	1373.5	1481.4	1586.9
44	452.6	595.9	735.7	872.2	1005.3	1135.3	1262.3	1386.3	1507.4	1625.8	1741.6
46	494.6	651.3	804.1	953.3	1098.8	1240.9	1379.6	1515.1	1647.6	1777.0	1903.5
48	538.6	709.2	875.6	1037.9	1196.4	1351.1	1502.2	1649.8	1794.0	1934.9	2072.7
50	584.4	769.5	950.1	1126.2	1298.2	1466.0	1630.0	1790.1	1946.6	2099.5	2249.0
52	632.1	832.3	1027.6	1218.1	1404.1	1585.7	1763.0	1936.2	2105.4	2270.8	2432.5
54	681.7	897.6	1108.2	1313.6	1514.2	1710.0	1901.2	2088.0	2270.5	2448.8	2623.2
56	733.1	965.3	1191.8	1412.8	1628.4	1839.0	2044.6	2245.5	2441.8	2633.6	2821.1
58	786.4	1035.5	1278.4	1515.5	1746.8	1972.7	2193.3	2408.8	2619.3	2825.1	3026.2
60	841.6	1108.1	1368.1	1621.8	1869.4	2111.1	2347.2	2577.7	2803.1	3023.3	3238.5

APPENDIX 2

Plot-Tree	Volume (m3)						
	3D Forest		Edit Surroundings		Edit Out Branches		
	DBH RHT	DBH LSR	DBH RHT	DBH LSR	DBH RHT	DBH LSR	Manual
W02-45	374.91	370.68			374.91	370.68	457
W03-03	283.31	4166.56	310.32	340.34	277.34	335.92	478.96
W04-74	229.04	7501.81	178.42	229.57	197.29	167.88	297.31
W05-05	886.71	1109.69			918.66	1108.86	1148.17
W06-48	222.87	309.18			222.87	309.18	668.06
W07-27	706.22	16472.63	613.24	739.84	609.42	735.23	967.45
W08-38	154.01	154.41			154.01	154.41	279.12
W09-03	1306.74	1335.74			1306.74	1335.74	825.82
W11-11	4211	4523.65	772.71	838.98	514.79	1160.22	232.59
W12-75	242.9	15484.16	318.14	414.73	318.14	414.73	480.88
W13-28	554.14	564.06			554.38	959.34	509.18
W16-61	1772.11	2299.9			2185.46	2145.66	2107.12
W17-02	420.46	459.08			420.46	459.08	795.23

APPENDIX 3

Plot	Tree	Method	Points	Height	Length	DBH RHT	DBH LSR
W02	45	Lowest Point	4530731	20.57	20.78	22.6	22.472
W02	45	**Position RHT**	4530731	20.57	20.78	22.6	22.472
W02	45	**Edited Away Branches**	3369149	20.57	20.78	22.6	22.472
W03	3	Lowest Point	1277903	16.63	16.78	21.6	82.834
W03	3	**Position RHT**	1277903	16.63	16.78	21.6	82.834
W03	3	**Edited**	1203210	16.64	16.6	22.6	23.668
W03	3	**Edited Away Branches**	580906	16.58	15588463	21.4	23.552
W04	74	Lowest Point	706587	16.67	16.7	19.4	111.028
W04	74	**Position RHT**	706587	16.67	16.7	19.4	111.028
W04	74	**Edited**	533575	12.68	12.77	19.4	22.006
W04	74	**Edited Away Branches**	436511	12.68	15588470	20.4	18.818
W05	5	Lowest Point	1196225	22.22	22.57	33.6	37.588
W05	5	**Position RHT**	1196225	22.22	22.57	33.6	37.588
W05	5	**Edited Away Branches**	726693	22.22	21.97	34.2	37.574
W06	48	Lowest Point	1539840	22.98	23.04	16.6	19.552
W06	48	**Position RHT**	1539840	22.98	23.04	16.6	19.552
W06	48	**Edited Away Branches**	1265338	22.98	23.03	16.6	19.552
W07	27	Lowest Point	3120363	23.62	23.78	29.2	141.024
W07	27	**Position RHT**	3120363	23.62	23.78	29.2	141.024
W07	27	**Edited**	2525116	23.64	23.51	27.2	29.876
W07	27	**Edited Away Branches**	2193344	23.47	22.86	27.2	29.876
W08	38	Lowest Point	2505751	17.92	18.08	15.4	15.42
W08	38	**Position RHT**	2505751	17.92	18.08	15.4	15.42
W08	38	**Edited Away Branches**	1869821	17.92	17.63	15.4	15.42
W09	3	Lowest Point	2080089	25.24	25.35	38.6	39.026
W09	3	**Position RHT**	2080089	25.24	25.35	38.6	39.026
W09	3	**Edited Away Branches**	1938301	25.24	15588449	38.6	39.026
W11	11	Lowest Point	1735384	15.33	15.42	86.4	89.55
W11	11	**Position RHT**	1735384	15.33	15.42	86.4	89.55
W11	11	**Edited**	1387461	15.34	15.42	37	38.554
W11	11	**Edited Away Branches**	803172	15.34	15.36	30.2	45.338
W12	75	Lowest Point	1661308	21.07	21.38	18	143.714
W12	75	**Position RHT**	1661308	21.07	21.38	18	143.714
W12	75	**Edited**	1634348	21.07	21.38	20.6	23.52
W12	75	**Edited Away Branches**	1314338	21.07	15588456	20.6	23.52
W13	28	Lowest Point	3667441	20.7	20.94	27.4	27.644
W13	28	**Position RHT**	3667441	20.7	20.94	27.4	27.644
W13	28	**Edited Away Branches**	921827	20.71	20.77	27.4	36.044
W16	61	Lowest Point	940284	26.82	26.22	43.8	49.898
W16	61	**Position RHT**	940284	26.82	26.22	43.8	49.898
W16	61	**Edited Away Branches**	647049	26.11	15588635	49.2	48.75
W17	2	Lowest Point	3387271	23.94	24.04	22.4	23.406
W17	2	**Position RHT**	3387271	23.94	24.04	22.4	23.406
W17	2	**Edited Away Branches**	2353808	23.94	15588639	22.4	23.406

APPENDIX 4

Plot	Tree	Method	Height	DBH	Stem Curve Results								
W02	45	Manual Stem Analysis	20.48	25.0	24	21.9	20.9	19.8	18.5	16.3	14.1	9.8	4.9
W03	3	Manual Stem Analysis	16.61	28.1	26.1	24.8	21.7	19.2	17.3	14.1	11	7.3	3.2
W04	74	Manual Stem Analysis	15.87	22.6	20.8	19.1	18.1	16.8	14.7	12.8	9.9	6.6	3.4
W05	5	Manual Stem Analysis	22.81	37.8	33.8	31.5	30	27.9	25.5	22.7	19.3	13.2	5.9
W06	48	Manual Stem Analysis	23.62	28.4	26.3	25.1	23.9	22.2	20.2	18.6	16.1	12.1	6.3
W07	27	Manual Stem Analysis	24.4	33.7	30.5	27.6	26.2	24.3	23.9	20.4	16.9	13.9	7.3
W08	38	Manual Stem Analysis	17.6	20.9	19.8	19	17.8	16.6	15.2	13.4	11	7.4	4.4
W09	3	Manual Stem Analysis	25.6	30.5	28.4	26.6	24.9	23.5	21.5	20.3	16	11.9	6
W11	11	Manual Stem Analysis	16.39	19.7	18.9	18.2	17.2	16.1	15.2	12.7	9.9	6.5	3.3
W12	75	Manual Stem Analysis	21.12	25.3	23.5	21.9	20.8	20.6	17.8	15.8	13.1	9.6	5.1
W13	28	Manual Stem Analysis	18.66	27.5	25.3	24.4	23.2	22.6	19.5	17.3	14	9.5	4.5
W16	61	Manual Stem Analysis	26.25	48.2	43.4	39.3	38.4	35.9	32.3	28.8	24.4	18.6	8.3
W17	2	Manual Stem Analysis	23.95	30.8	28.1	25.9	24.1	22.4	21.2	19.1	16.6	11.9	6