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REPORT

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ENHANCING FOREST INVENTORY WITH TLIDAR

EXECUTIVE SUMMARY

The purpose of this project was to use the existing growth and yield plot network to explore the use of terrestrial LiDAR (tLiDAR) to both collect growth and yield information more efficiently and collect the information so that it could be used as calibration data for an aerial LiDAR inventory. The project collected far more data than can be analyzed here, but this was done intentionally to allow for mining of the data as processing techniques and algorithms are developed. While many studies have been conducted in plantation forests or ideal understory conditions, this study focused on natural forest stands. The goal was to target mixedwood forest conditions, as they represent a major portion of the Ontario woodbasket and tend to be the least understood. The tLiDAR used in this study was the FARO M70, which was used by a field crew hired for this project and not a team of researchers. The goal was to see if the unit could survive a field season and see if the technology could be applied by staff with reasonable training and not heavily invested researchers. The results showed that there are significant challenges to deploying the technology, both from an operations and data analysis perspective. In operation, the data is subject to occlusions from understory as well as branches blocking calibration targets. Environmental factors like rain or wind can effect the overall quality of the data and may be hidden by the processing conducted by the software. The data processing side represents a challenge in both computing power and time, as the data is extremely dense and requires significant time to process. This can mean that small changes you wish to make to all scans will require a significant time investment to rerun. This will change as automation routines are developed but are currently limiting. The results show that there is still a long way to go to replacing boots on the ground in mixedwood forest conditions, but the data collected can be refined and rerun as techniques and software develops. Combining tLiDAR with complimentary 360 degree images and drones allows a crew to collect a suite of information in a short period of time and may facilitate the automated extraction of some or all metrics in the future.

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PROJECT OBJECTIVE

The purpose of this project was to use the existing growth and yield plot network to explore the use of terrestrial LiDAR (tLiDAR) to both collect growth and yield information more efficiently and collect the information so that it could be used as calibration data for an aerial LiDAR inventory. The project aimed to identify what parts of the current growth and yield program could transition to tLiDAR collection to increase efficiency of the current ground-based data collection process. It also explored the idea of using these same plots as calibration data for the aerial LiDAR being flown in the next round of the Enhanced Forest Resource Inventory (eFRI).

DELIVERABLES

This project generated a vast quantity of data that far exceeds the project scope. This was intentional to allow further research into which growth and yield metrics can be yielded from both terrestrial and aerial LiDAR, as well as exploring the integration of drone technology and 360 degree cameras. The project scope for the purposes of this final report are limited to diameter at breast height and tree height, as those were the targeted features of interest. A full copy of all the data collected is stored with the OMNRF as well as at the Lakehead University Centre for the Application of Resources Information Systems or LU-CARIS. At the time of this report generation, the aerial LiDAR was not yet available but the overlapping plots are identified in the Project Location section below. The intent of this project is to make all data freely accessible with no restriction, as long as all derivative products remain open source (see end user licence agreement before downloading data).

PROJECT DESCRIPTION

Field-based growth and yield information is collected across multiple plot networks in Ontario to address provincial monitoring and modelling commitments/obligations (Declaration Order MNR-75 condition 49). This data is imperative to understanding forest compositional changes over time and the effects of climate change. It is used in the forest management planning process to translate eFRI information into empirical yield curves, used to predict sustainable wood supply and confirm long-term management direction (LTMD). Ensuring these networks have a suitable number of plots to capture landscape variability and are re-measured on an appropriate cycle to accurately reflect stand succession and rate of change is a financial challenge. tLiDAR may provide similar or better accuracy as conventional field measurements with respect to volume metrics (e.g. heights, diameters, tree taper, crown form/coverage, cull, piece size) and decrease the time required to measure a plot through automation. This project aimed to find efficiencies in the growth and yield program methodology and subsequently reduce the cost per plot. This data can then potentially be used to calibrate any subsequent eFRI aerial LiDAR product, further improving the accuracy of our provincial growth models and remotely sensed forest resource inventories.

The new eFRI product, particularly the acquisition of aerial LiDAR, requires an accuracy assessment to be completed using ground verified data. The ground-based data from the growth and yield plot

network can provide calibration information to aid in this process and help identify which conditions can be described using remotely sensed information (e.g. even aged, single-species stands) and which conditions require ground-based data (e.g. complex, multi-species stands). With Ontario poised to transition to a raster-based inventory, with a focus on automation and aerial LiDAR, this project provides a case-study in overlapping datasets to allow for the calibration and refinement of automated tools to aid in this process.

By assessing the viability of tLiDAR for this type of inventory, Canada can begin to look at the national forest inventory plot network and assess if the same process can be applied. Several European countries use tLiDAR for calibration and growth and yield style plots, with some moving to the idea of a harmonized plot network to inform both national and regional needs (Bienert et al 2006, Maas et al 2007, Trochta et al 2013, Trochta et al 2017). This data can help scientists understand how trees respond to climate change. If growth and yield programs were able to transition to tLiDAR capture, then more time efficient re-measurements would provide an understanding of absolute growth change along the entire stem profile and thus improving taper models and stand level volume estimates. This improved and more accurate volume estimate can be correlated with climatic variables and trends across different climate zones. Aerial LiDAR alone does not provide this type of information.

The Growth and Yield program must utilize emerging technologies to provide more accurate and time efficient information. The eFRI program must also seek similar objectives, so the best available information can be provided to the forest industry once the two data streams from each program are combined. Industry will benefit by increased alignment between volume and piece-size metrics collected on the ground, with attributes reported in an inventory product. The tLiDAR data has the potential to provide the necessary information to translate/align the data between the two programs. This will benefit economic development corporations looking to attract forest based industries who require more accurate and detailed information on volume than is supplied by the current inventory product.

Academic institutions will benefit by having access to a dataset that currently does not exist in the Canadian context. This data can be used by students who can mine it and work on refining techniques to improve its application even further. This includes the emerging areas of machine learning and deep learning classification techniques, which rely on large datasets to develop relationships and classify in an automated way.

PROJECT TEAM

Alexander Bilyk served as the project lead. He is a graduate of the Masters of Science in Forestry from Lakehead University and is currently pursuing a PhD in enhanced forest inventory at Lakehead University while continuing to work full time. His company, Overstory Consultants, was the proponent in this project and is focused on providing remote sensing solutions to clients across Canada. He has specialized in industrial remote sensing and maintains his skills by teaching the remote sensing courses at Lakehead as a sessional lecturer. Alexander served as the project manager and performed all of the data analysis work.

Christopher Stratton is the Growth and Yield Forest Productivity Specialist for Northwestern Ontario within the Ministry of Natural Resources and Forestry. He has a wealth of knowledge and experience delivering the current growth and yield program, as well as administering the national forest inventory plot measurements in the region. He has a diverse background in Ecological Land Classification, silviculture, and sampling techniques used to study the effects of forest management on a variety of wildlife species. Christopher served as the field manager and trained the field staff in all growth and yield field measurement protocols, as well as managing logistics and provided project support.

The field crew hired for this project represent the future of field personnel in the forest industry. They were Alexandra Campbell and Mike Ferrari (pictured here). Mike has previously worked in the growth and yield program, while Alexandra was working in it for the first time but had extensive field experience. Their job, aside from collecting all field information and running the tLiDAR, was to provide realistic feedback and project design suggestions to the research team.

A second growth and yield field crew, comprised of Justin Hunter-Bechard and Darcy Richard, provided additional support to help reach the target field plots towards the end of the field season and also provided feedback on field operation of the tLiDAR unit.

DESIGN

This project will utilized the existing growth and yield plot network in the Dog River-Matawin forest. Resolute Forest Products (the SFL holder) was a partner on this initiative and utilizing the existing plot network allowed for the stratification of plots based on previously confirmed ground measurements. The re-measure data and tLiDAR data collected though this project were enriched from previous plot measures to provide a more descriptive context of forest stand dynamics. About a month into the project, the inventory branch of the OMNRF informed the project team that they would be able to coordinate capturing aerial LiDAR for the southern Dog-River Matawin forest. For this reason, the plots were selected to correspond to this area. The map shown in Figure 2 demonstrates the location of all study sites, with the tan area indicating the extent of the aerial LiDAR captured. All permanent growth plots (PGPs) are shown in blue and all permanent sample plots (PSPs) are shown in pink. Each PSP contains three PGPs within it. The sites shown outside the

aerial LiDAR zone were captured before the aerial LiDAR decision was made and are still used as part of this analysis.

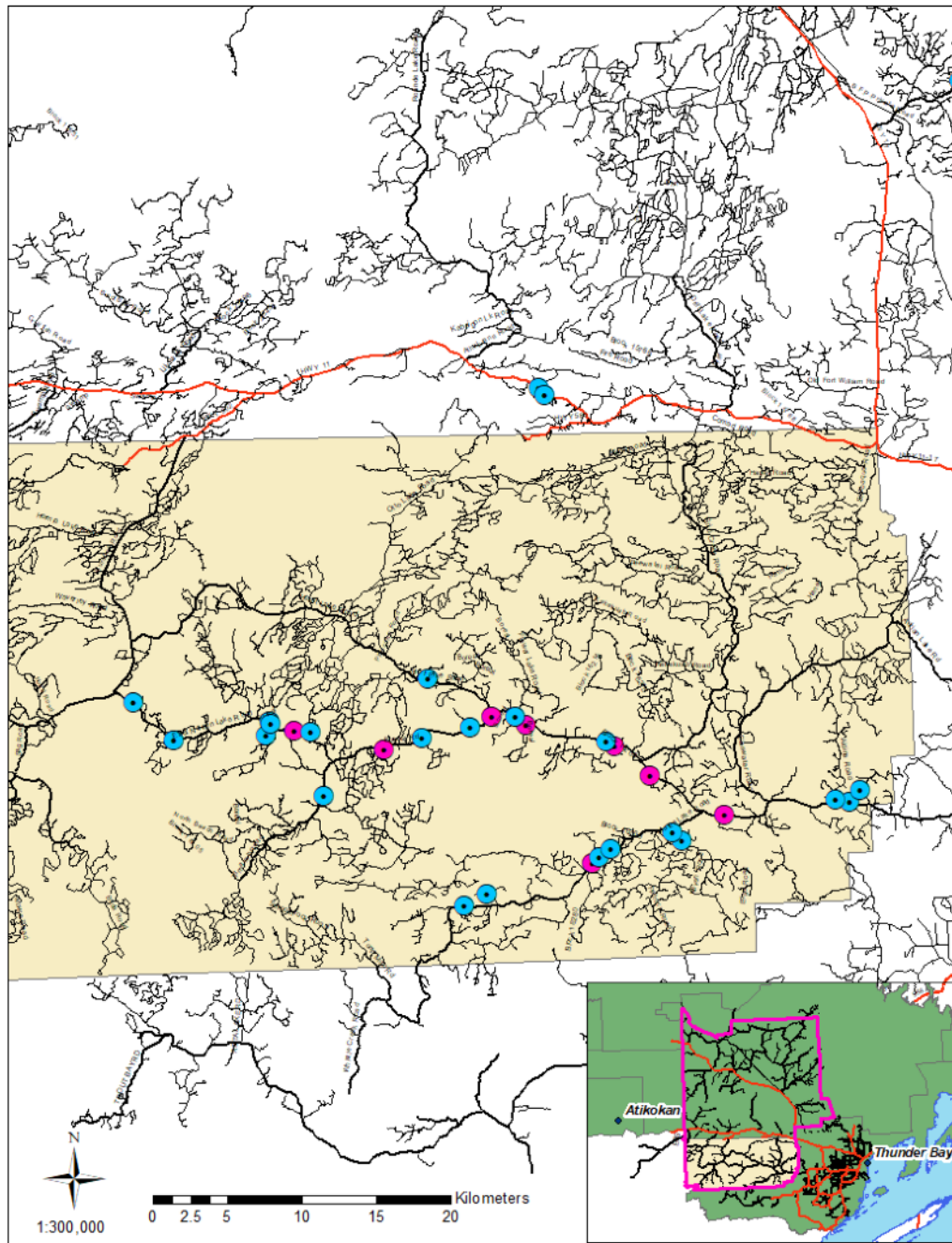Figure 1 - Plot Locations

The plots chosen were selected to cover a range of forest conditions, with a focus on Boreal mixedwoods. The breakdown of plot composition is shown in Table 1 below. Natural mixedwood conditions were targeted as they are not well represented in the literature and represent the third most common forest type in Ontario after conifer upland and lowland at approximately 18% of all

forests in Ontario (OMNR 2016). Mixedwoods represent an additional challenge to tLiDAR due to dense understory composition which can cause occlusions and prevent the scanner from measuring the full tree.

Table 1 - Plot Distribution by Working Group

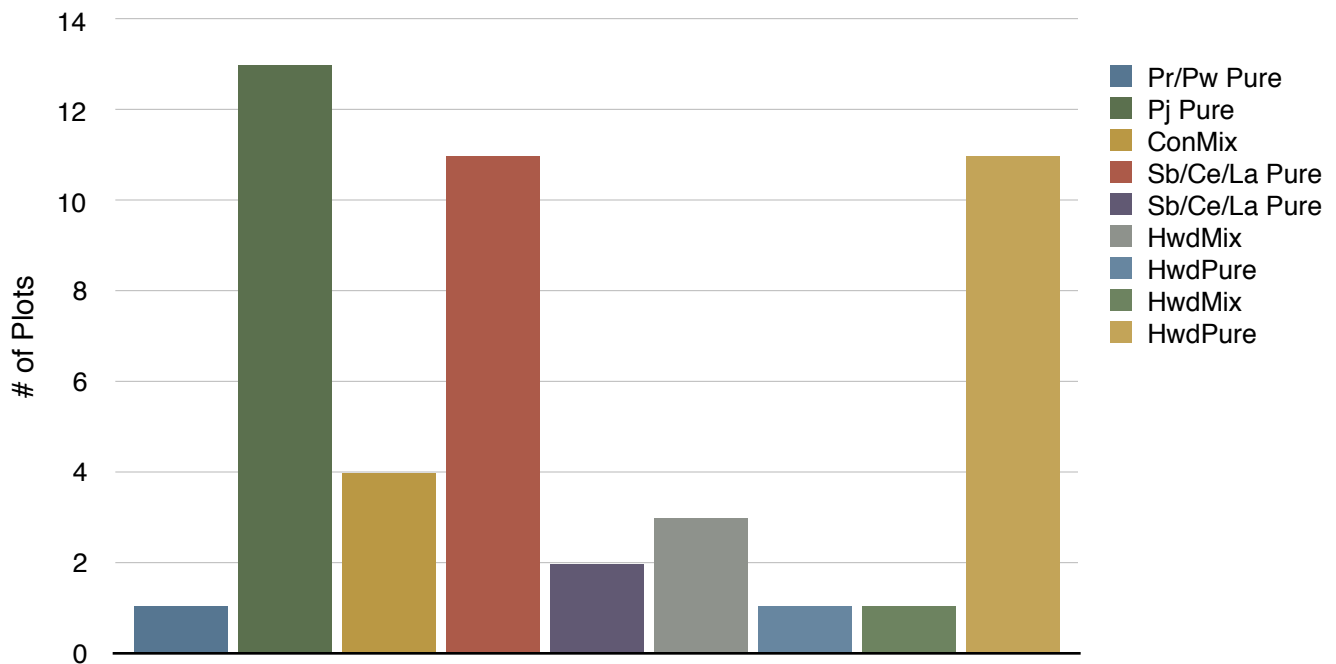| CompGroup	WG_Group	# of Plots
Pr/Pw Pure	2	1
Pj Pure	3	13
ConMix	12	4
Sb/Ce/La Pure	13	11
Sb/Ce/La Pure	20	2
HwdMix	38	3
HwdPure	45	1
HwdMix	70	1
HwdPure	74	11

Figure 2 - Frequency of Working Groups by Plot

MATERIALS

The tLiDAR unit chosen for this project was the FARO M70. This tLiDAR unit represents an excellent balance of form factor for field work with performance. At a weight of 4.2 kg, it was possible to pack the unit into a modified camera backpack for easy field transport. The beam accuracy is guaranteed to be within 3mm and the unit is IP54 rated. This means that while it is not rated for direct water immersion, rain does not affect the performance. This does not mean that rain does not influence the quality of the data, but the unit itself can get wet without suffering damage. The capability of the tLiDAR unit to survive a field season was one parameter being tested as part of this project, since a dedicated field crew was handling the unit, not the researchers. The unit was actively used in light to medium rain, as well as snow, and survived the entire field season with no damage.

To accompany the unit, a series of target spheres were required. These must be extremely precise, as they serve to calibrate the unit and snap the individual scans together into one larger pointcloud. The spheres chosen for this project were the SECO 100mm targets, as six could fit into a field pack and they represented a balance between price and quality. The target size proved to add some challenges, as outlined in the discussion.

Additional information was collected using 360 degree cameras and drones to augment the tLiDAR data. The cameras used were the Ricoh Theta SC and the GoPro Fusion. They represent two ends of the spectrum in terms of features and price for 360 cameras and allowed for the capture of hemispherical photos for canopy analysis.

The drone used for this project was the DJI Mavic Pro. It represents an excellent balance of performance and size, allowing the crew to carry the drone into the plot easily in their cruise vest if needed.

TLIDAR FIELD METHODOLOGY

This project was completed in two stages. The first stage was to set up a variety of sampling schemes with the tLiDAR at a few select growth and yield plots in close proximity to Thunder Bay. The distance between tLiDAR scans and their orientation was modified to look at the total scanning time required, area of the plot that is captured, etc. The intention was to have a central scan at plot center with a minimum of three additional scans arranged in a triangle pattern.

These additional scans were be conducted 12m away from the central scan location to ensure that a full 400m2 plot would be captured. If only a central scan is performed, the literature indicates that there will be shadows and missed trees resulting in a reduction of accuracy. These potential scanning setups were based on work done in Europe and were be done in both conifer and hardwood dominant stands (see Bienert et al 2006, Maas et al 2007, Trochta et al 2013, Trochta et al 2017). The final sampling design required four total scans. The first was at plot centre with the remaining three being conducted at north, 120 degrees and 240 degrees. The dedicated growth and yield team hired for this project were involved in this design process, as they were the ones conducting the scans in the field.

Stage two involved deploying the team to the selected plots. The crew would arrive at the site and identify all the scan locations. They would then hang the targets so that they could be seen by a minimum of two scan locations and thus be used for processing. While they did their best to make sure that the spheres were visible, this proved to be a critical step that caused errors later on, as the distribution of spheres was sometimes insufficient to allow the software to function. There was no hard rule for sphere placement as it does require judgement and context. Larger targets would aid in the errors encountered and make this easier in the future. The scans were then run at each location, taking 19 minutes and 30 seconds to complete each scan. The scan parameters are shown in Figure 3 below. The same settings were used for all scans conducted throughout the study and were a balance of precision and time.
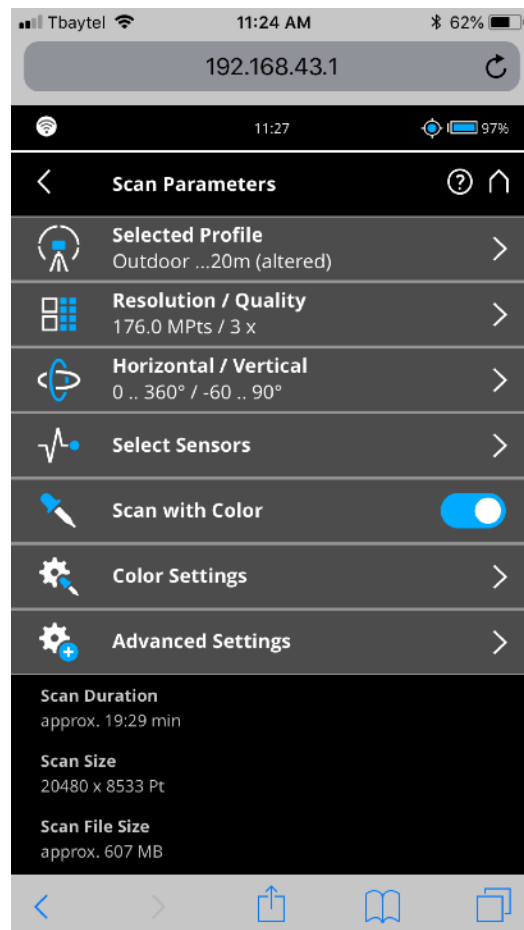

Figure 3 - Scanning Parameters

This two stage approach helped to identify any unanticipated unknowns before the technology was deployed at scale. Once all scans were completed, the trees in the plot were then manually measured in accordance with the growth and yield program plot methodology v2016 to allow for the accuracy assessment. The individual tree metrics include: species, diameter, height and crown ratio as they represent the most time intensive part of the Growth and Yield field program and have the highest likelihood of being captured with the tLiDAR unit.

TLIDAR PROCESSING STEPS

1. FARO Scene version 2018 was used to assemble all scans for a given PGP. The scans were imported and preprocessed.
2. After preprocessing, the scans were automatically aligned if spheres could be located. If they could not be located, the GPS information was used to roughly align the point clouds and then the cloud to cloud matching algorithms were used to align them
3. The accuracy of these matching efforts varied greatly and depended entirely on the visibility of the targets, as well as the noise of the surrounding vegetation

   It should be noted that FARO Scene does support importing the location of scans from external sources but the limitation is that the coordinates can only be applied to VISIBLE points! This was a major challenge since the scanner was placed over the plot centre post, which generates a blind spot directly below the scanner. Future versions of FARO scene are supposed to support manually assigning coordinates to scans regardless of point visibility but it is a current limitation and should be taken into consideration

4. Once the point clouds were aligned, a project point cloud was generated and then exported into .xyz format.

   The speed of processing is directly related to the computer being used so investment in a powerful computer with enough available resources to completely timely analysis is the key to implementing this technology at scale.

5. This .xyz point cloud was imported into CloudCompare V2.09 and exported as a .las file. This step was necessary as the .las file format exported from FARO Scene was not recognized by subsequent analysis software packages.
6. The .las file was imported into ArcGIS Pro and clipped to the plot boundary of 11.28m to form a 400m^2 plot.

TLIDAR ANALYSIS STEP

1. 3D forest version 0.42 was used for all of the analysis work. It was developed in the Czech Republic and is available as open source software from http://www.3dforest.eu
2. The .las file was imported into 3D forest and the terrain was automatically extracted
3. Once the terrain file was identified, the analyst would clean away any outlining points. These were usually artifacts from the edge of the plot and were obviously not part of the terrain.

4. The next step separates the vegetation into individual trees. This step takes the longest and represents the area of analysis where the biggest impact can be made. The average time to finish computing the tree separation was 4 hours, with some plots requiring more time. The reason for this was that each plot could contain upwards of 200 million points.
5. Once the separation of trees was completed, the lowest point could be computed. This tagged the bottom of each tree and allows for the computing of all subsequent parameters
6. The diameter at breast height (DBh) can be calculated two ways in 3D forest. The first is using the randomized Hough transformation. The second uses the least squares regression (LSR) to identify DBh. The math behind each of these methods is well documented in the user manual. The challenge that the LSR method faces is that it is prone to picking up branches and including them in the stem if they overhang at the 1.3m height.
7. The tree height and length were also computed. The difference between the two tools is that the height is looking at the vertical height, while length can account for leaning trees.
8. The data was then exported into a txt file with all parameters attached to each "tree."
9. Due to time constraints, no additional cleaning steps were undertaken for this project but results could be dramatically improved if the time was taken to remove outlying branches and shrubs.

ADDITIONAL FIELD METHODOLOGY

In addition to tLiDAR, the team also tested using 360 degree cameras and drones to capture complementary data. We set out to see if the technology could be used to augment or replace some of the current growth and yield metrics. The steps involved in the collection of this information are outlined below.

360 IMAGE PROCESSING

1. The images were downloaded from both the Ricoh Theta SC and the GoPro Fusion
2. The Ricoh images required no additional processing and were renamed to the appropriate plot number and tagged with _RICOH at the end of the filename
3. The GoPro Fusion takes two separate images which must be processed into one continuous image. This was completed in GoPro Fusion Studio 1.3. Once assembled, the images were named appropriately and tagged with _GoPro at the end of the filename. The original files are stored in a gopro_raw_files subfolder (see data structure I)
4. For simple viewing, the Ricoh Theta

APPENDIX

app can be

downloaded for free on both windows and mac and allows for the viewing of the 360 images, with full panning supported.

5. If there was a question around which plot the photos came from, it is possible to use the "Photo to Point" tool in ArcGIS toolbox to generate a shape file from the GPS information in the photos. It should be noted that the GoPro has an internal GPS, while the Ricoh uses the location of the phone that triggers it, not it's own internal GPS.

6. The images were then processed in StereoPhotoMaker to reproject them into the hemispherical style photo shown above.
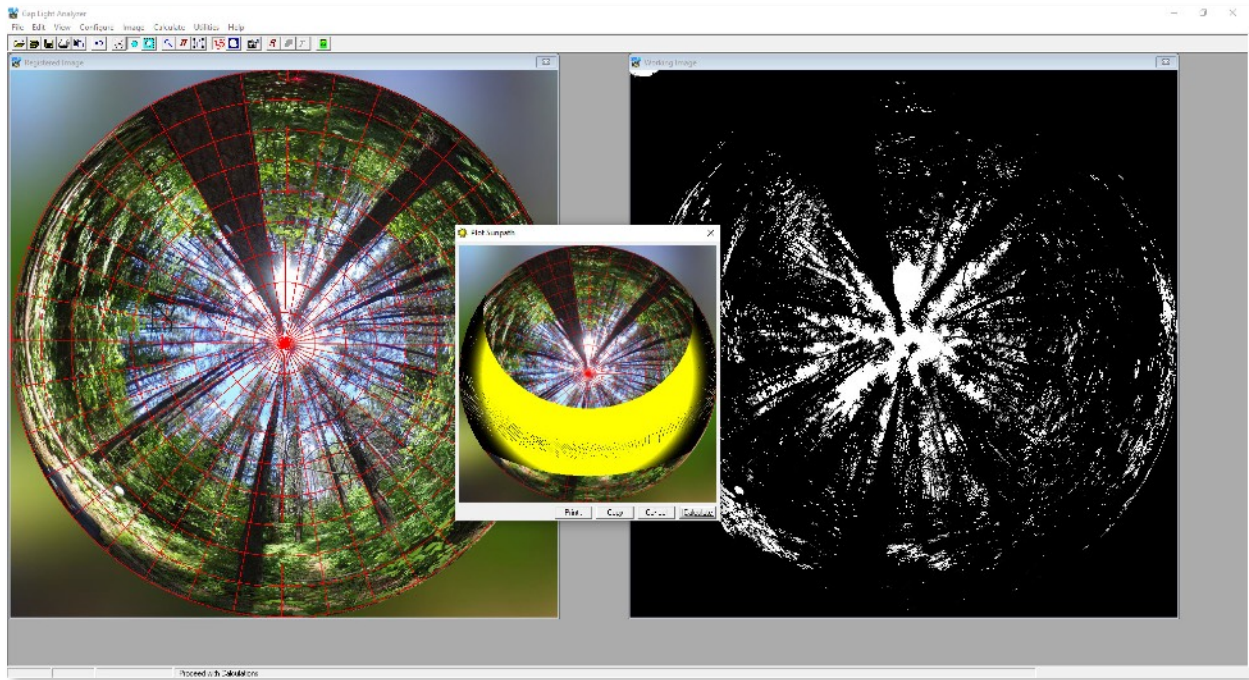

Figure 4 - Gap Light Analyzer Example

7. These reprojected images were then imported into Gap Light Analyzer, a free tool which allows for the quantitative analysis of crown closure, among other indices (See Figure 4).

8. This data has not been fully analyzed but will be used to assess crown closure as part of an undergraduate thesis effort in 2019-2020.

DRONE IMAGE ACQUISITION AND PROCESSING

1. As mentioned previously, the DJI Mavic Pro was used for all image acquisition in this project. It was chosen for it's excellent flight characteristics and small form factor. All images were acquired using the MapPilot application on an iPad. The application supports automated flight, and allowed the user to collect the full plot area in 1-2 batteries, depending on environmental conditions.

2. A double-grid mission was used to cover the plot area and ensure complete coverage. The flight mission was set to have 85% forward overlap between photos and 80% sidelap between flight lines. Figure 5 below demonstrates what this looked like.
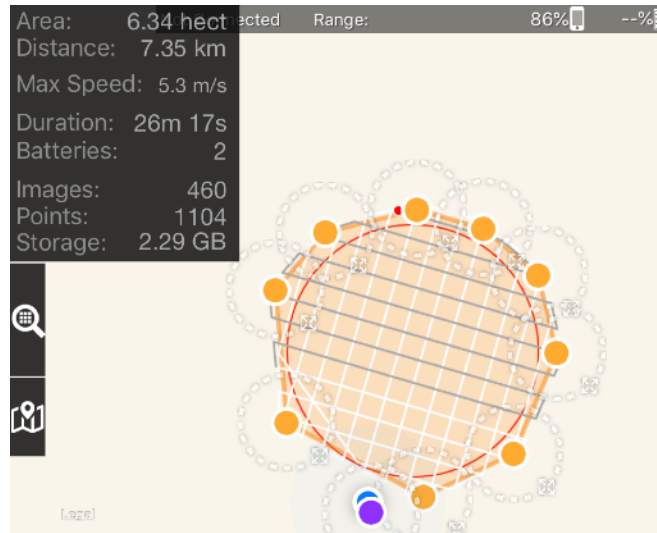
Figure 5 - Double Grid Mission in MapPilot

3. Once the mission was uploaded, the drone would fly itself and take the images. If it was getting close to running out of power, it would return to home and request a new battery then continue where it left off. All of the plots were buffered to account for GPS errors and uploaded as a KML file for offline use
4. The images were then copied off the SD card and stored as per Appendix I.
5. The images were then processed in Agisoft, now known as Metashape.
6. The processing parameters were:
   i. Alignment - Medium
   ii. Dense Cloud Quality - Medium
   iii. Surface reconstruction - height field - dense cloud
   iv. Orthomosaic - exported with WGS 84 projection
7. The results were then exported and the orthomosaic was clipped to the plot extent
8. The resulting canopy point cloud is demonstrated in Figure 6 below.
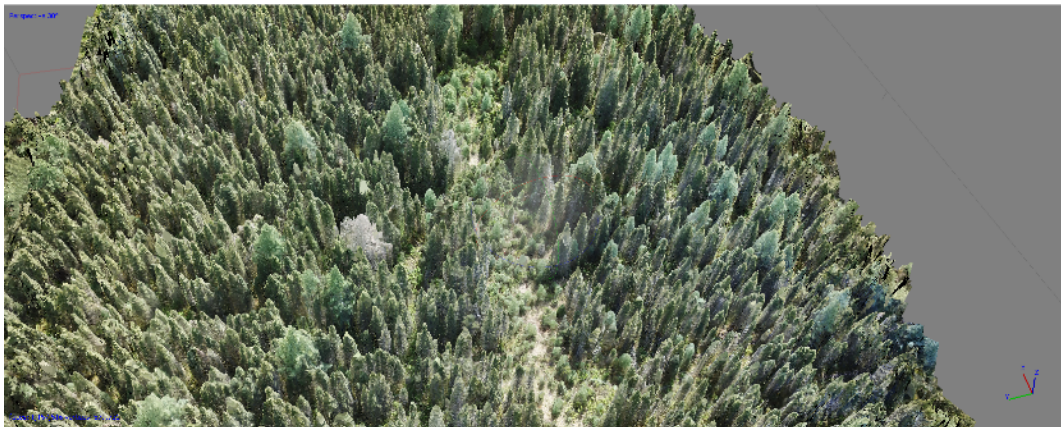

Figure 6 - Drone derived canopy model

This drone derived data provides another layer of information for analysis as well as context for the site. It can also provide a way of understanding how trees are falling out of the canopy as part of forest succession. To this end, all plots are being flown in the summer of 2019 with the DJI Mavic Enterprise dual drone. This drone is capable of capturing thermal data, which preliminary research within LU-CARIS has been shown to identify dead standing trees. If we are able to add mortality into the equation with drones, it may help speed up the acquisition of this important metric for forest succession. It should be noted that in the case of four plots, the images were not able to be processed due to the appearance of snow and the lack of distinguishing features. The solution to this would be to deploy some targets or fly the area when there is no snow on the ground.

RESULTS

The results for the 3D Forest derived metrics vs. the field metrics are shown in the tables below. As you will see, there is a statistically significant difference across all metrics between tLiDAR and field measurements. It is important to note that due to the time and budgetary constraints, no filtering was done on the point cloud to remove branches or shrubs. It should also be noted that due to a lack of stem mapping, and not every plot having the tree numbers painted prior to tLiDAR acquisition, the results have been rolled up to the plot level and do not compare individual tree-to-tree measurements. The average value for DBH and HT is used as height is not sampled for every tree on the plot in the field.

Table 2 - Tree Count Comparison

PlotName	# of Trees Identified in 3D Forest	# of Actual Trees (not null dbh) from 3D Forest	# of Trees Measured in the Field
FCBOW56-012-0PGP	145	103	118
FCBOW56-016-0PGP	131	105	114
FCBOW56-029-0PGP	93	67	108
FCBOW56-036-0PGP	72	53	57
FCBOW56-037-0PGP	111	98	183
FCBOW56-038-0PGP	95	68	106
FCBOW56-043-0PGP	112	78	108
FCBOW56-060-0PGP	93	61	73
FCBOW56-061-0PGP	111	85	154
FCBOW56-2003-013PGP	107	89	96
FCBOW56-2003-014PGP	68	49	133
FCBOW_TBW-2004-01PGP	85	73	121
FCBOW_TBW-2004-02PGP	91	83	178

FCBOW56-2004-06PGP	121	104	140
FCBOW56-2004-08PGP	108	78	128
FCBOW56-2004-09PGP	119	99	75
FCBOW56-2004-11PGP	103	82	90
FCBOW56-2005-03PGP	107	97	235
FCBOW56-2005-04PGP	122	103	142
FCBOW56-2005-05PGP	99	73	70
FCBOW56-2005-12PGP	74	50	70
FCBOW56-2005-13PGP	70	52	154
FCBOW56-2005-14PGP	82	72	270
THU2007002PGP	63	57	62
THU2007003PGP	51	45	49
THU2007004PGP	57	17	15
THU2007005PGP	61	13	13
THU2007006PGP	48	16	17
TBP1992005PSP-gp1	86	61	70
TBP1992005PSP-gp2	114	86	130
TBP1992005PSP-gp3	86	61	219
TBP1995001PSP-gp1	95	75	121
TBP1995001PSP-gp2	47	39	99
TBP1995001PSP-gp3	76	62	92
TBP1995006PSP-gp1	154	124	204
TBP1995006PSP-gp2	153	139	245
TBP1995006PSP-gp3	112	90	247
TBP1995007PSP-gp1	100	84	71
TBP1995007PSP-gp2	125	98	43
TBP1995007PSP-gp3	92	81	67
TBP1995008PSP-gp1	76	52	115
TBP1995008PSP-gp2	68	42	134
TBP1995008PSP-gp3	94	67	153
TBP1995009PSP-gp1	94	71	129

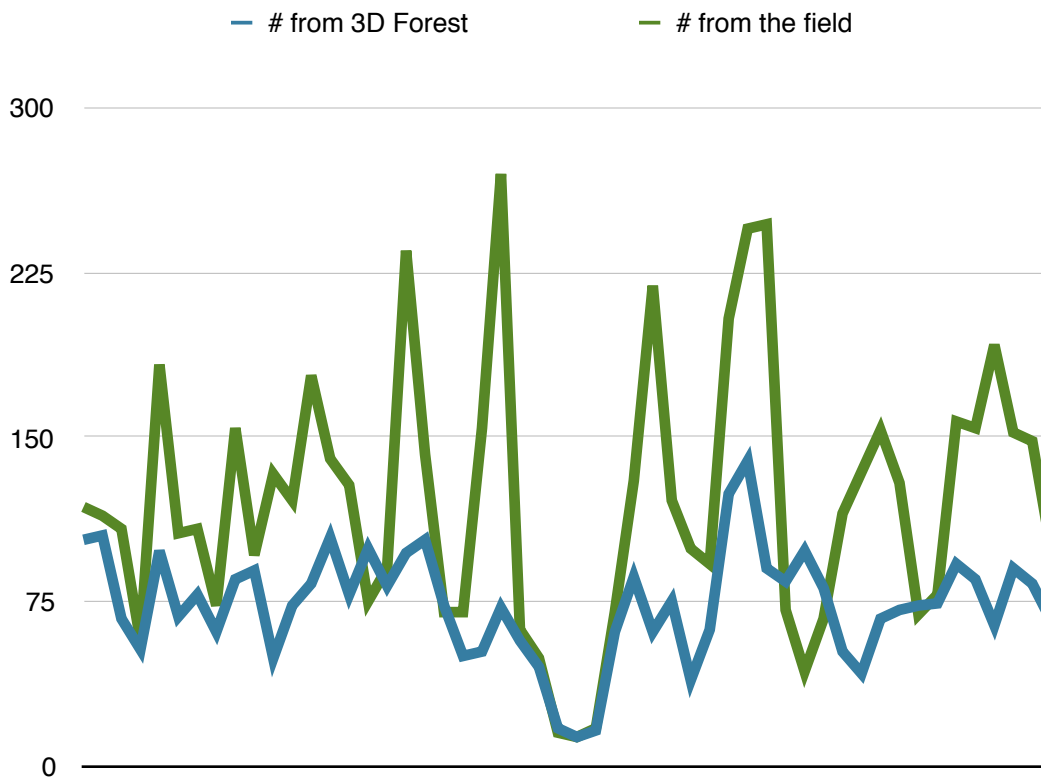|			
TBP1995009PSP-gp2	111	73	69
TBP1995009PSP-gp3	98	74	78
TBP1995010PSP-gp1	110	92	157
TBP1995010PSP-gp2	105	85	154
TBP1995010PSP-gp3	82	64	192
TBP1997002PSP-gp1	108	90	152
TBP1997002PSP-gp2	96	83	148
TBP1997002PSP-gp3	95	66	98

Figure 7 - 3D Forest vs Field Tree Count by Plot

Table 3 - Average DbH Comparison

PlotName	Average DBH_HT	Average DBH_LSR	Field Measured Average DBH
FCBOW56-012-0PGP	32.11	69.47	15.20
FCBOW56-016-0PGP	20.32	53.62	13.10
FCBOW56-029-0PGP	62.61	109.64	8.73
FCBOW56-036-0PGP	78.37	163.21	10.70
FCBOW56-037-0PGP	15.25	56.73	12.33
FCBOW56-038-0PGP	47.72	79.71	12.80
FCBOW56-043-0PGP	56.04	94.14	11.28
FCBOW56-060-0PGP	56.20	97.36	11.26
FCBOW56-061-0PGP	32.63	93.58	9.37
FCBOW56-2003-013PGP	46.35	99.20	13.72
FCBOW56-2003-014PGP	60.43	147.81	8.72
FCBOW_TBW-2004-01PGP	52.69	99.75	11.64
FCBOW_TBW-2004-02PGP	31.39	78.01	10.35
FCBOW56-2004-06PGP	34.77	84.25	13.05
FCBOW56-2004-08PGP	38.65	67.15	12.11
FCBOW56-2004-09PGP	51.69	91.72	12.47
FCBOW56-2004-11PGP	33.37	66.86	15.48
FCBOW56-2005-03PGP	49.58	122.68	8.32
FCBOW56-2005-04PGP	41.27	86.27	8.70
FCBOW56-2005-05PGP	33.55	195.10	12.81
FCBOW56-2005-12PGP	64.43	119.77	16.47
FCBOW56-2005-13PGP	244.67	103.82	8.77
FCBOW56-2005-14PGP	50.32	100.99	6.21
THU2007002PGP	18.44	20.29	20.85
THU2007003PGP	21.00	27.71	20.69
THU2007004PGP	37.27	52.39	38.27
THU2007005PGP	38.57	46.43	40.06
THU2007006PGP	38.24	38.24	37.64
TBP1992005PSP-gp1	63.65	160.43	12.84

TBP1992005PSP-gp2	70.40	136.41	8.43
TBP1992005PSP-gp3	66.21	137.62	6.40
TBP1995001PSP-gp1	87.39	119.93	11.75
TBP1995001PSP-gp2	61.47	99.20	12.26
TBP1995001PSP-gp3	57.10	92.83	14.06
TBP1995006PSP-gp1	47.78	67.63	8.20
TBP1995006PSP-gp2	18.29	54.28	7.19
TBP1995006PSP-gp3	22.25	62.03	6.83
TBP1995007PSP-gp1	55.01	88.11	14.44
TBP1995007PSP-gp2	31.74	99.28	17.91
TBP1995007PSP-gp3	35.94	83.25	17.86
TBP1995008PSP-gp1	64.85	94.03	7.00
TBP1995008PSP-gp2	44.51	95.17	7.79
TBP1995008PSP-gp3	57.60	112.33	7.16
TBP1995009PSP-gp1	33.47	95.53	12.81
TBP1995009PSP-gp2	44.29	99.05	15.87
TBP1995009PSP-gp3	27.76	65.36	17.46
TBP1995010PSP-gp1	20.47	125.37	12.24
TBP1995010PSP-gp2	38.83	108.90	10.97
TBP1995010PSP-gp3	39.30	104.89	8.78
TBP1997002PSP-gp1	31.94	104.38	12.06
TBP1997002PSP-gp2	28.61	66.80	12.74
TBP1997002PSP-gp3	47.82	275.25	15.59

Table 4 - Average Height Comparison

PlotName	Average Height	Average Length	Field Measured Average Ht
FCBOW56-012-0PGP	7.27	7.41	16.93
FCBOW56-016-0PGP	5.58	5.60	13.72
FCBOW56-029-0PGP	5.74	6.08	20.28
FCBOW56-036-0PGP	4.79	5.30	15.52

FCBOW56-037-0PGP	7.11	7.26	16.34
FCBOW56-038-0PGP	8.25	8.51	14.83
FCBOW56-043-0PGP	4.64	5.04	17.21
FCBOW56-060-0PGP	4.28	4.64	10.92
FCBOW56-061-0PGP	5.42	5.60	13.28
FCBOW56-2003-013PGP	7.98	8.31	16.10
FCBOW56-2003-014PGP	5.74	6.13	18.42
FCBOW_TBW-2004-01PGP	5.36	5.65	14.36
FCBOW_TBW-2004-02PGP	5.41	5.53	14.48
FCBOW56-2004-06PGP	6.08	6.28	16.31
FCBOW56-2004-08PGP	5.98	6.21	19.22
FCBOW56-2004-09PGP	4.81	5.18	15.49
FCBOW56-2004-11PGP	10.65	10.80	16.10
FCBOW56-2005-03PGP	4.17	4.42	10.03
FCBOW56-2005-04PGP	4.49	4.62	9.47
FCBOW56-2005-05PGP	5.38	5.65	9.76
FCBOW56-2005-12PGP	4.34	4.75	13.38
FCBOW56-2005-13PGP	5.28	5.65	8.93
FCBOW56-2005-14PGP	3.76	4.03	7.12
THU2007002PGP	14.95	15.02	19.04
THU2007003PGP	13.05	13.16	17.86
THU2007004PGP	19.27	19.59	26.23
THU2007005PGP	20.33	20.54	26.35
THU2007006PGP	21.17	21.31	25.73
TBP1992005PSP-gp1	5.17	5.43	12.28
TBP1992005PSP-gp2	4.18	4.45	9.07
TBP1992005PSP-gp3	4.81	5.13	9.64
TBP1995001PSP-gp1	4.74	4.94	13.89
TBP1995001PSP-gp2	4.73	4.92	11.55
TBP1995001PSP-gp3	4.18	4.61	11.53
TBP1995006PSP-gp1	4.87	4.94	11.57

TBP1995006PSP-gp2	5.99	6.04	9.74
TBP1995006PSP-gp3	4.18	4.22	9.88
TBP1995007PSP-gp1	7.37	7.54	20.00
TBP1995007PSP-gp2	5.99	6.23	15.49
TBP1995007PSP-gp3	6.92	7.33	20.88
TBP1995008PSP-gp1	5.47	5.60	9.31
TBP1995008PSP-gp2	5.45	5.62	9.93
TBP1995008PSP-gp3	5.30	5.38	9.42
TBP1995009PSP-gp1	6.75	6.88	14.27
TBP1995009PSP-gp2	6.04	6.37	13.80
TBP1995009PSP-gp3	7.69	8.01	16.30
TBP1995010PSP-gp1	4.99	5.14	13.34
TBP1995010PSP-gp2	4.70	4.93	12.63
TBP1995010PSP-gp3	5.44	5.80	11.79
TBP1997002PSP-gp1	5.35	5.51	14.62
TBP1997002PSP-gp2	7.39	7.50	14.57
TBP1997002PSP-gp3	5.78	6.03	14.62

DISCUSSION

As noted throughout the methods and results section, this project was a first step in a long road to developing the field and analysis tools to deploy tLiDAR into natural forest stands. The literature to date has focused on plantation forests or ideal conditions where the issues are minimized. By targeting completely natural stands, this project aimed to see just how successful the off the shelf technology would be right now. The results clearly demonstrate that we have a long way to go still. The best results are those from plots located with the Hogarth plantation owned by Lakehead University. They are numbered as *THU2007XXXPGP* and demonstrate the capability of the technology in ideal conditions. With every metric of interest showing a statistically significant difference in a t-test (see Appendix II), the results demonstrate that changes are needed in both the field and analysis. The project was limited by the funds available for analysis and all steps that could be taken were within the timeframe available. The possibility remains open to further analyze the results and try and get closer to the field numbers by cleaning up outliers and removing noise from the dataset.

The two biggest challenges to success in the field are (1) the size/number of the target spheres and (2) the distribution of scans within the plot. The targets chosen were the 100mm SECO spheres. As

shown in the image to the left, they pack up into a compact field case and were selected for their portability and relative affordability. It should be noted that the pack of 6 was $1,200, so moving to larger targets or increasing the number of targets will come with additional expense. The targets are also fragile, and they suffered some significant damage during the field season that renders them unusable for future work. The spheres are not able to survive repeated drops and develop significant chipping, which causes them to reflect the laser in different directions and not perform their job. The size issue becomes a challenge when branches get in the way and block some or all of the sphere. FARO Scene expects the sphere to be a certain size and relies on a certain number of laser pulse hits per sphere to use them as targets. Even if the operator tries to override the software and manually identify a sphere, it may refuse if there is an inadequate number of returns. Increasing the target size will increase the chances of getting sufficient returns to have a viable target and some experiments will need to be conducted to determine substitutes. The challenge is that the tolerances of the targets are so tight that an error of a few mm on the target can translate to centimetres of error within the point cloud.

The distribution of scans within the plot came about from testing in the early summer and preliminary results were promising. With the growth and yield specification requiring an error within 3mm, the scanner settings were targeting achieving that goal within a reasonable amount of time. As the scan resolution increases, the time to complete a scan increases with it. After discussing the challenges encountered with other tLiDAR researchers in the Czech Republic, they suggested modifying future scanning setups to increase the number of perimeter scans (Figure 8).
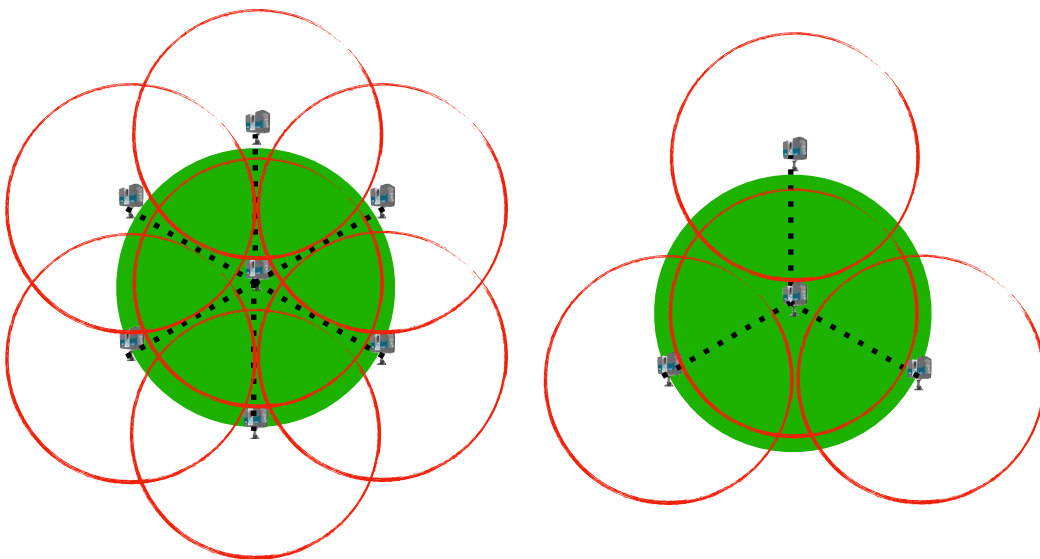

Figure 8 - Comparison of scanning methods

This would require dropping the individual scan resolution by half to 6mm accuracy but would balance out with the increased angles on each object so that it should result in better results with less missing data. Figure 8 demonstrates how this would function as the increased overlap should result in an overall accuracy closer to the growth and yield specification. The goal is to try and keep the overall scanning time down to approximately 2 hours per growth plot, including the time to move between scan positions. This was identified as a good target as it should allow crews to measure two plots a day instead of the current one.

In terms of the stem mapping challenge identified, there are two solutions which may help with that. The first would be to implement a rule where the scans take place after the paint has been refreshed on the site. While this did occur on some sites, not all plots were painted prior to scanning. Even on sites where the paint did occur first, it was sometimes obscured by other trees or by the angle on which it was painted. To avoid this, the ideal solution would be to have a full stem map of the plot. The challenge is that this is very time consuming to produce and is only done in the tolerant hardwoods of southern Ontario. There is however a possible technology to help aid in this and it is based on proven Vertex technology. It is called the Haglof PosTex and it uses three of the traditional vertex receivers in a triangular setup (see Figure 9).

Figure 9 - Haglof PosTex

The system works by sending a pulse into the central prism at plot centre. This prism splits the signal to each receiver and a software modification on the Vertex allows it to understand how the delay in respond from each receiver translates into a distance and bearing from plot centre. There is one receiver that is always oriented North so the proper bearings are assigned each time. This technology is outlined in Lämås 2010, where he discusses the use of this setup to position stems in a single person survey. The total setup cost is about a thousand USD higher than purchasing a Vertex alone and represents a possible solution to the stem analysis orientation problem. Accurate

positioning of measurements from ground data and terrestrial LiDAR need this level of precision and this tool may allow the information

Another challenge of tLiDAR is the effect of wind. This problem is actually two-fold, as it is possible for the analyst to miss the problem entirely. Figure 10 demonstrates the phenomenon where the tLiDAR scan captures a moving tree top but the colour photos captured to colourize the scan hide the error. For this reason, it is highly recommended to process all scans without colour to check for this problem, then colourize as the final step before export.
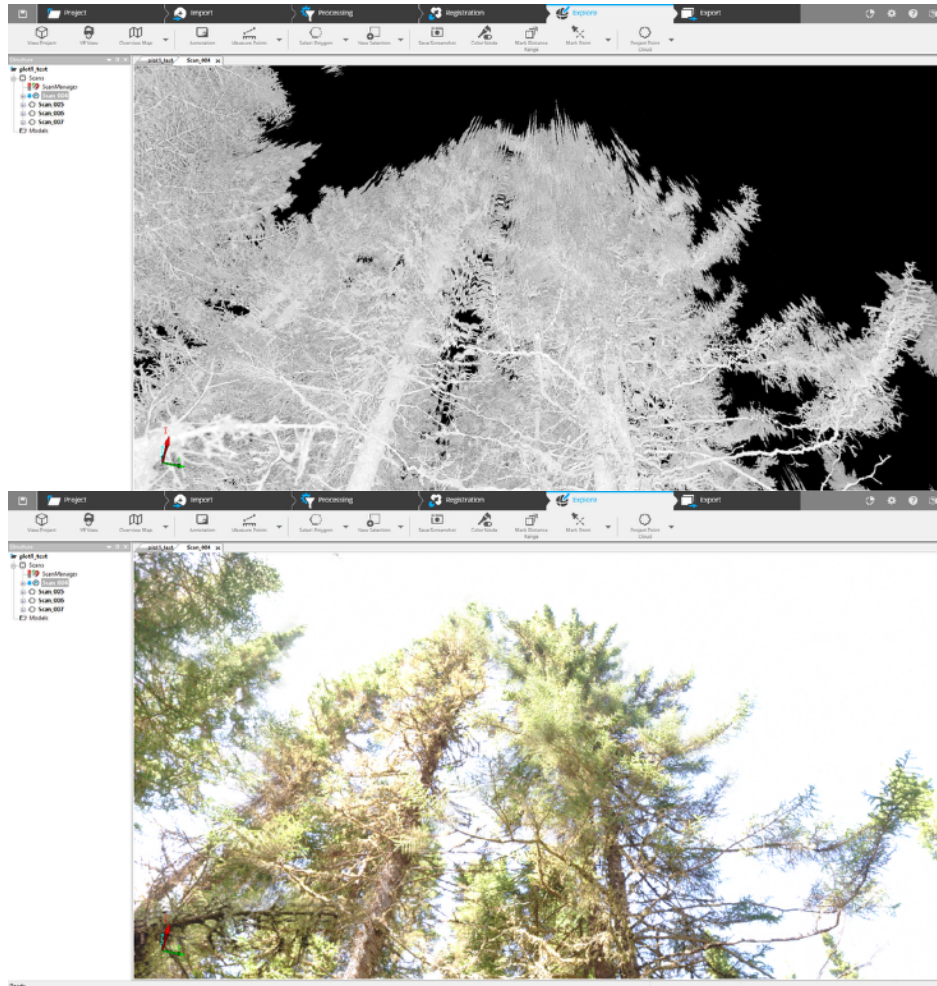
Figure 10 - Wind Issue

It is also possible that the sensor has a glitch. For this reason it is necessary to examine the results while in the field. Figure 11 demonstrates a situation where the mirror must have skipped a position and captured an error. There is no post-processing fix to this and the error must be lived with. The FARO scanner is equipped with a screen for scan previewing and care must be taken to ensure that the results are as intended before moving on.

Figure 11 - Sensor Error

Another occasional error experienced when exporting from FARO Scene was the incomplete export of the .xyz data. The final point cloud was usually in the 8-15 gigabyte range, depending on the understory density. As shown in Figure 12, the same file exported two different times yields very different final products. It was necessary to test every exported file to make sure that the full cloud exported. The errors were random in nature and did not seem to correspond to any limitation in the computer. It is simply an error that must be checked for before proceeding.

Figure 12 - File Export Error

KNOWLEDGE AND TECHNOLOGY TRANSFER

The results of this project have already been disseminated in a variety of formats. The first was in an OMNRF Science and Research Branch internal article in the summer of 2018. The project overview and preliminary results were also presented at the International IUFRO Conference "Landscape Management: From Data to Decision" in Prague, Czech Republic in September of 2018. As tLiDAR has been used extensively in Czech Republic, there were several researchers who were able to provide direction and suggestions for improving our results. The forest conditions in Europe are ideal compared to the natural conditions we have to contend with, so it presents a unique opportunity for collaboration and development.

Alex Bilyk will also be competing in the Ontario 3 Minute Thesis Competition in April 2019, where this project will be summarized in 3 minutes or less!

Presentation at IUFRO, Prague 2018

The final results of this study will be published in Alex Bilyk's ongoing PhD with Dr. Pulkki as a full Chapter as well as in scientific journals. As part of this effort, two oral presentations have been accepted to be presented at the IUFRO World Forestry Congress in Brazil 2019. They will focus on the utilization of consumer grade 360 degree cameras for canopy structure analysis and the use of thermal drones for mapping tree mortality.

The results of this project are also being communicated in an OMNRF Science and Research Branch seminar, schedule for April 18, 2019. This seminar is open to anyone who wishes to participate and will be webcast. The purpose is to showcase the results and facilitate a discussion on the potential applications and challenges of using tLiDAR for growth and yield as well as forest inventory.

FUTURE WORK

As machine learning algorithms mature, it is anticipated that this data will be mined for further metrics, including automated species classification, horizontal and vertical forest structure classification and potentially ELC classification. The tLiDAR scans provide a record that can be revisited and refined over time, a feature that current field methods do not allow for.