LiDAR Derived Individual Tree, Hexagon, and Polygonal Forest Inventories

ROMEO MALETTE FOREST

Version 1.0

Project 1669-2

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Contents

List of Figures

List of Tables

List of Acronyms and Definitions

AOI	Area Of Interest. Also referred to as the Project Area.
ABA	Area Based Analysis. Can refer to a raster or pixel value.
HEX	Reference to Hexagonal inventory product. Seamless area-based inventory.
ITC	Individual Tree Crown inventory. Similar to ITI.
ITI	Individual Tree Inventory. No distinction between the point and polygon feature classes.
Segmentation	Process of delineating individual stems from the LiDAR point cloud.
TSI	‘Tree Species Identifier’ software.
ESA	European Space Agency

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1 Introduction

1.1 BACKGROUND

Ontario's Forest Resource Inventory (FRI) is the primary input to the Forest Management Plan (FMP) process, where key strategic objectives and indicators for planning purposes are derived from the use of key inventory attributes such as tree species and stand age. However, for operational decision-making, more detailed inventories can be key, and go beyond the current capabilities of our Ontario forest inventories. To bridge this gap in the currently available inventory products, in this project we used a multi-scale inventory process to create a new breed of inventory that meets all the strategic needs for use in an FMP in Ontario, as well as provide additional attributes and details that enable tactical and operational planning.

1.2 OBJECTIVES

This project aimed to use remote sensing data, forestry knowledge, and data science to build forest inventory products for 100,000 hectares of the Romeo Malette Forest that will function at both operational and strategic forest planning scales. These products include:

1. An individual tree inventory (ITI) that locates and attributes individual trees with species, height, DBH, and volume.
2. A 400m^2 tile (hexagon) based inventory that uses ground plots and traditional LiDAR EFI approaches along with aggregated ITI data to assign species, volume, height, basal area, crown cover, etc.
3. A FIM compliant polygon inventory appropriate for strategic modeling. This includes a process for representing non forest areas, and young forest areas with silviculture records.

1.3 PROJECT AREA BOUNDARY

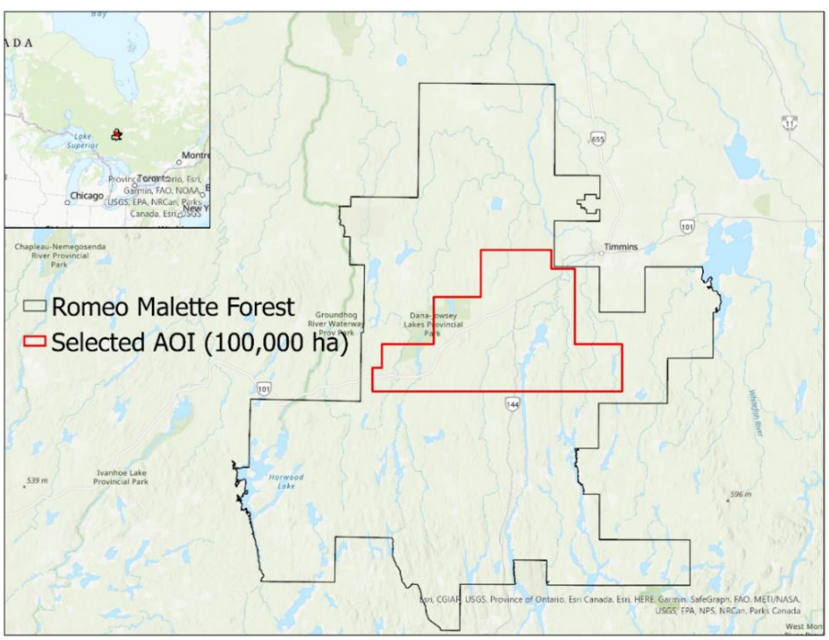

Figure 1. Romeo Malette Forest project area boundary.

2 Data

2.1 ONTARIO SINGLE PHOTON LIDAR

The leaf-on single photon LiDAR data was acquired over the Romeo Malette Forest in June and July of 2018 using the Leica SPL-100 sensor. The SPL-100 data was collected in parallel flight lines with 50% swath overlap at a nominal altitude of 3360 m above ground level and a nominal speed of 350 km/h from a Piper-PA-31-350 aircraft. The data was pre-processed by the data provider following the guidelines of Gluckman (2016[1]) and delivered as a set of de-noised, georeferenced and classified point clouds (LAS v1.4 format). A summary of the SPL-100 instrument characteristics and acquisitions parameters is provided in Queinnec et al., 2021[2].

Table 1. Summary of SPL100 characteristics and acquisition parameters. Adapted from Queinnec et al., 2021.

RMF 2018 Acquisition Parameters	
Nominal flying altitude	3660 m AGL
Nominal flying speed	350 km/h (180 knots)
Field of view	30◦
Average swath width	2000 m
Overlap between flightlines	50%
Pulse repetition frequency	60 kHz (6 MHz considering the 10 × 10 array)
Average point density	40.8 pts/m2
Average ground returns density	4.0 pts/m2
SPL 100 Technical Specifications	
Transmitted wavelength	532 nm
Beam configuration	10 × 10 array
Beam divergence (1/e2)	0.08 mrad
Scanning pattern	Conical

2.1 ONTARIO DIGITAL IMAGERY

The leaf-on digital aerial imagery were acquired over the Romeo Malette Forest in June and July of 2018 using the Leica ADS-80 sensor. These data were acquired in a 4 – band configuration (blue, green, red, near-infrared) at a ground sample distance of 20 cm.

2.2 SATELLITE STACK

Sentinel 2 A/B satellite imagery data was acquired for the project area to create additional descriptors for use in the inventory process. Approximately 507 individual tiles between 2017 01 01 and 2021 07 04 with a reported cloud cover of less than 35% were selected and processed for the project. A bandwise filtering process was

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[1] Gluckman,J.,2016.Design of the processing chain for a high-altitude, airborne, single photon lidar mapping instrument ,In: Turner , M.D. ,Kamer-man ,G.W.(Eds.), Laser Radar Technology and Applications XXI. SPIE, p.983203. https://doi.org/10.1117/12.2219760

[2] Queinnec, Martin & Coops, Nicholas & White, Joanne & McCartney, Grant & Sinclair, Ian. (2021). Developing a forest inventory approach using airborne single photon lidar data: from ground plot selection to forest attribute prediction. Forestry: An International Journal of Forest Research. 10.1093/forestry/cpab051.

deployed using this dense set of observations to arrive at stable pixel values. Seasonally centred mosaics at 10m and 20m resolutions were created, with source resolution determined by input bands (bands B02, B03, B04 and B08 have a source resolution of 10m while B05, B06, B07, B8A, B11 and B12 have a source resolution of 20m). A set of dimensionality reduced bands were produced for direct use in the species prediction model. Additionally, standalone predictions of Softwood Percent, a binary Hardwood/Softwood 'Lead' and Lead Species predictions were all produced via Random Forest Regression/Classification processes using the Sentinel 2 data. All satellite inputs were subject to the individual tree species prediction feature importance / feature masking process and useful descriptors were carried through the species prediction process.

2.3 VEGETATION SAMPLING NETWORK (VSN) FIELD PLOTS

The field calibration plots were collected using the Ontario Ministry of Natural Resources and Forestry (MNRF) Vegetation Sampling Network Protocol: Technical specifications for field plots (SRB-Technical Manual-10). The plots were collected between July and November of 2019 by Sumac Geomatics as a part of KTTD project 18-2018. A total of 250 plots were established using a structurally guided sampling approach and principal components analysis outlined in Queinnec et al (2021) to accurately represent the range of forest structure on the RMF. This plot network is composed of remeasured existing plots (89) and newly established plots (161). The plots are 11.28m radius (400m^2) in size and record the species, height and DBH of all live and dead trees with DBH >=7.1 cm. Tree height was measured with the Nikon Forestry Pro Laser and Haglof Vertex IV hypsometers. Plot-level attributes such as stand development stage were also assessed (Queinnec et al., 2021).

3 Methodology

3.1 INDIVIDUAL TREE INVENTORY

The primary goal of the Individual Tree Inventory (ITI) phase was to identify, segment and correctly classify stems greater than or equal to 10m in height and attempt to classify stems greater than 5m in height. Identifying and classifying these individual stems facilitates an operational scale inventory and creates the foundational inputs from which to build the Hexagon and strategic Polygonal inventories from. To achieve these goals, the ITI phase required LiDAR Analysts to segment individual trees from the LiDAR point cloud. The Timber Species Identifier (TSI) software then created a polygon feature (record) for each tree crown and calculates a number of basic attributes including tree height, ground slope/aspect/elevation, crown area, live crown percentage, and local stem density. Each tree also received a unique ID at this point in the process.

3.1.1 Stem Segmentation

The segmentation process is the identification of individual trees within the 3D point cloud as separate features. Although there are several segmentation methods available within the public domain, this project used a proprietary segmentation routine within the TSI software suite.

The segmentation parameters used were selected based on a variety of stand characteristics including density, ecosite composition, coniferous and deciduous proportions, and other regional attributes. Generally, the TSI segmentation method uses classic watershed techniques in addition to cluster finding routines.

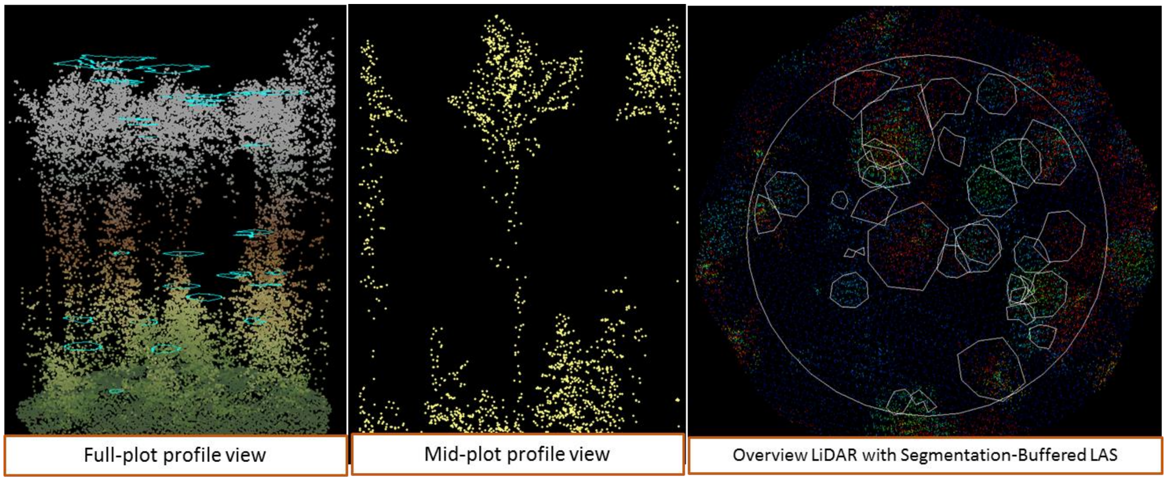


Figure 2. Segmentation Sample of Multi-story Stand (polygons indicate segmented stems).

3.1.2 Calibration and Validation Data Capture

3.1.2.1 INDIVIDUAL TREE SAMPLES

Individual tree samples were collected to establish a training database of known species throughout the project area. These trees became training and validation trees for the machine learning algorithm, and it is critical during this step that the samples are spatially matched with 100% accuracy to the applicable stem in the LiDAR point cloud. Using stereo photography, sample stems for each species were located at the interpreter's discretion based on Forest Ecosystem Classification (FEC), stand structure, spatial distribution, stand density and stem height. By capturing a large number of samples, it allowed for a subset of the trees to be set aside from model building and used for model validation purposes. A total of 5097 individual stem samples were collected across the project AOI.

A quality assurance step is completed after the interpreter has identified the individual tree samples. An analyst confirms that each sample stem is correctly matched within the corresponding LiDAR point cloud and determines that the intended species attribution is correct based on experience and visual indicators. Once this quality assurance step is complete, the stem is confirmed to be used as a calibration or validation sample.

3.1.2.2 VALIDATION AREAS

A total of 162 one (1) hectare validation areas (Figure 3) are then analyzed over the project area by an interpreter using digital stereo photography. The interpreter has discretion to move a validation area to a nearby location that better suits the intended results of the exercise. The segmentation within the validation area is analyzed and the sample area is attributed with a species composition based on the sum of individual tree crown areas. This step helps ensure that the individual tree species prediction model is not overfitting to the training trees and the results reflect the project area as a whole.

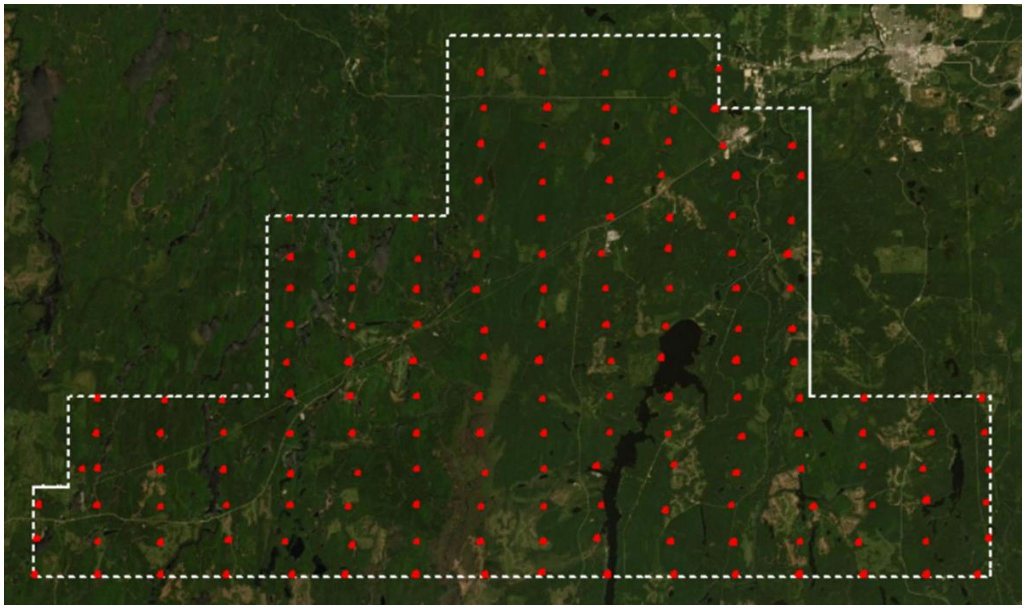


Figure 3. Validation areas.

3.1.3 Species Prediction

Models are then developed based on training/validation data to determine species prediction for each tree. The TSI software performs a discrete analysis of each tree in the project area and measures each stem's associated geometry, density, reflectivity, and imagery characteristics against that of the known trees. The TSI model then determines the best matching species for each segmented tree. A probability score is calculated representing the strength of signal and is reported for the species within the project species database (Table 2).

Table 2. Example of a Species Probability Matrix within the TSI software.

Tree ID	SPECIES	SPECIES_RANK	SPECIES_PROBABILITY_1	SPECIES_PROBABILITY_2	SPECIES_PROBABILITY_3
DF-932_194	bw	bw_ab_bf	0.401016	0.241733	0.090893
DF-932_195	bw	bw_bf_la	0.199105	0.180569	0.150334
DD-932_203	ab	ab_bw_la	0.207781	0.162366	0.144167
DD-932_204	bw	bw_cw_sb	0.35052	0.182521	0.079489
DF-932_210	bw	bw_ab_mr	0.465598	0.091374	0.088124
DH-932_212	cw	cw_la_sb	0.512888	0.133477	0.095069
DD-932_214	ab	ab_bw_la	0.456892	0.183963	0.076537
DH-932_218	la	la_bf_sb	0.698065	0.099906	0.056306
DJ-932_222	cw	cw_bf_la	0.231819	0.230579	0.197008
DJ-932_223	cw	cw_bw_la	0.377056	0.130814	0.109144
DD-932_228	ab	ab_bw_sb	0.552894	0.14772	0.053736
DF-932_234	bw	bw_pt_mr	0.531388	0.205544	0.06786
DH-932_236	cw	cw_la_bw	0.407607	0.274713	0.079439
GE-1016_4007	cw	cw_la_ab	0.995445	0.000901	0.000849

The difference between a given probability score and that of the next closest species candidate can help characterize the confidence of the software's species prediction. A large difference between the selected species score and other species scores result in a 'high confidence tree'. Note that this metric measures the software's confidence relative to the sample tree library developed specifically for the project and not the actual probability that the species is correct or incorrect. For example, Tree GE-1016_4007 in Table 2 was identified as cw with high confidence based on a 0.995 score compared to the next highest of la with a 0.000901 score. Tree DD-932_204 was identified as bw comparatively with a lower confidence on a 0.350 score compared to the next highest cw with a 0.183 score.

The individual training stems are used to drive the machine learning prediction process, while the validation areas are used to 'tune' the model to ensure the specific training trees produce a result that fits the landbase as a whole. Figure 4 below illustrated the end result of that training process across all 162 one-hectare validation areas. Overall, TSI is finding a very similar species breakdown by canopy cover to what was stereo interpreted in the validation areas.

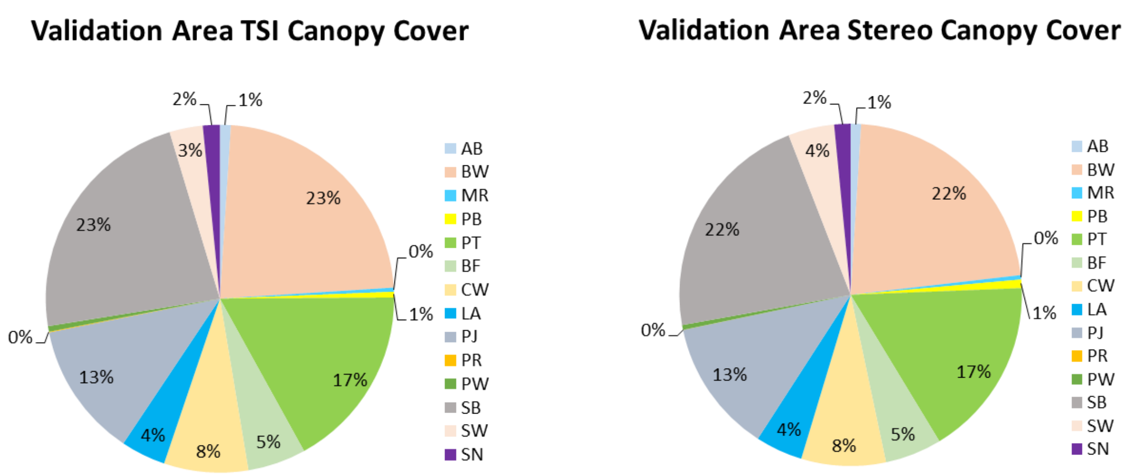


Figure 4. Predicted (TSI) vs Photo interpreted species proportion in 162 validation areas used to help train the species prediction model.

3.1.4 Species Prediction Accuracy

An independent assessment of species accuracy is completed using a set of photo interpreted individual trees. The species assigned by the interpreter is compared to the species call assigned to the tree by the prediction process (TSI software) and is shown in the table below (Table 3).

This stem test is a comprehensive assessment of prediction accuracy and included 2,863 trees. It includes samples > 5m in height. The mix of species samples does not represent the overall species mix present on the land base since species accuracy is not meant to consider how common it is on the land base.

Overall, species accuracy at the tree level was 78%. Strengths include good separation of conifer and deciduous species (97%) and good separation of live from dead trees (99%). Issues included some overcalling of white birch and black spruce, although black spruce has good weighted average scores. As expected, overall accuracies are highest for the largest trees. The <10m accuracy is above expectations at 78% primarily due to the lack of diversity in that height group.

Table 3. Species prediction accuracy for individual trees in the ITI.

		TSI															
		BF	CW	LA	PJ	PR	PW	SB	SW	AB	BW	MR	PB	PT	SN	Total	Hit rate (Correct/ Photo Interp)
Photo Interpreter	BF	184	5	0	4	0	0	26	1	0	2	0	0	0	0	222	83%
	CW	2	162	2	1	0	0	4	2	1	11	0	0	0	0	185	88%
	LA	9	1	170	7	0	0	34	2	0	1	0	0	0	0	224	76%
	PJ	5	2	1	281	2	0	57	1	0	8	0	0	7	0	364	77%
	PR	0	0	0	8	29	1	0	2	0	1	0	0	0	0	41	71%
	PW	0	0	2	3	0	113	3	5	0	1	0	0	0	0	127	89%
	SB	24	0	9	13	0	1	410	15	0	4	0	0	0	2	478	86%
	SW	4	1	0	2	0	5	22	125	0	3	0	0	0	0	162	77%
	AB	0	0	0	0	0	0	0	0	89	12	1	0	1	0	103	86%
	BW	2	6	1	5	0	0	2	0	7	230	1	18	24	1	297	77%
	MR	2	2	0	0	0	0	0	0	4	22	22	0	5	0	57	39%
	PB	0	2	0	1	0	0	2	0	1	35	1	62	80	0	184	34%
	PT	0	0	0	3	0	0	2	1	1	22	0	13	227	0	269	84%
	SN	0	2	0	5	0	0	4	0	0	1	0	0	6	132	150	88%
Total		232	183	185	333	31	120	566	154	103	353	25	93	350	135	**2863**	**78%**
Precision (Correct/ TSI)		79%	89%	92%	84%	94%	94%	72%	81%	86%	65%	88%	67%	65%	98%		
Weighted Avg (Hit rate & Precision)		**81%**	**88%**	**83%**	**81%**	**81%**	**91%**	**79%**	**79%**	**86%**	**71%**	**54%**	**45%**	**73%**	**93%**		

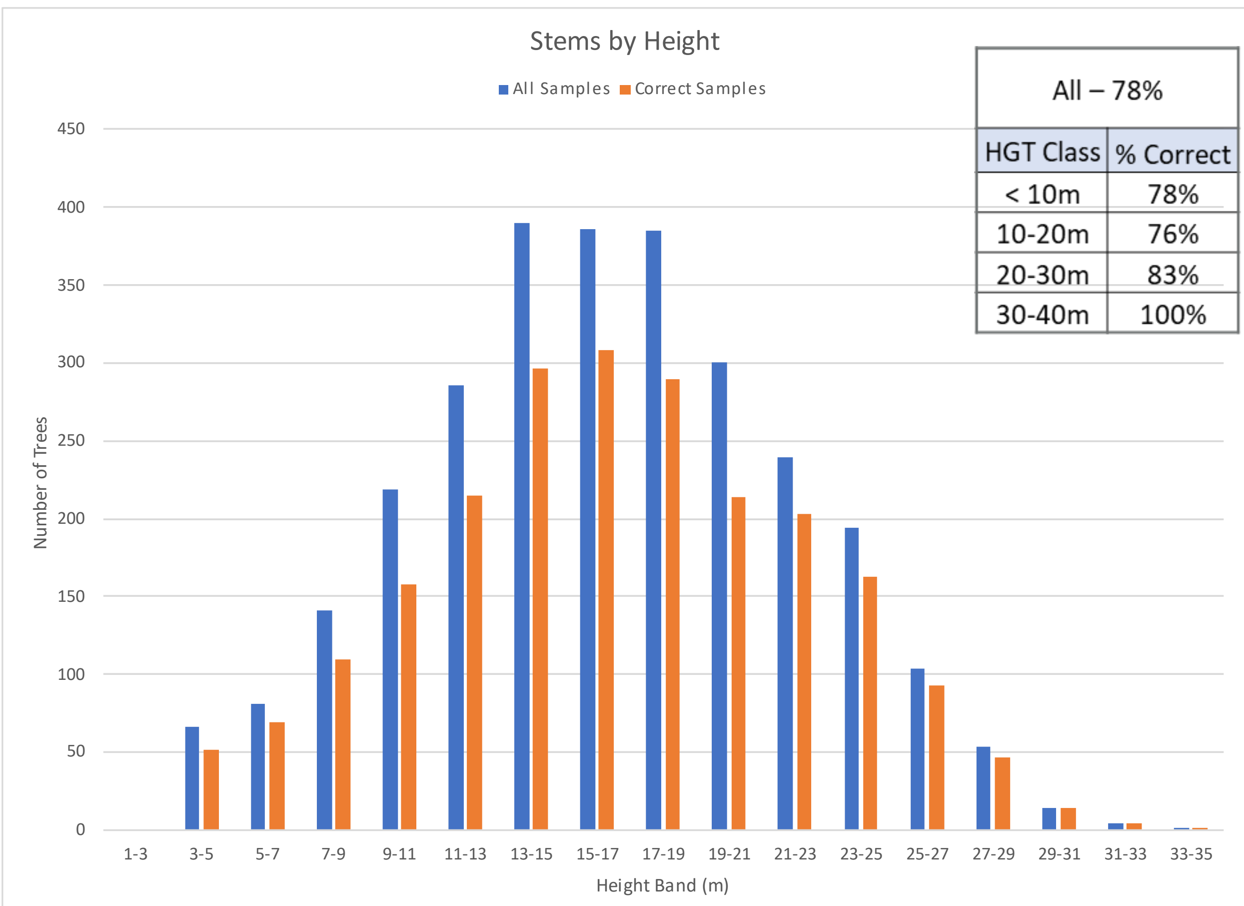


Figure 5. Species predicted correctly at the tree level in 2 m height classes.

3.1.5 Diameter at Breast Height

Predicting diameter at breast height (DBH) follows the 2016 study completed by Shongming Huang (Alberta Agriculture and Forestry) which uses a nonlinear least squares method (Huang and Yang 2016). The developed equation predicts DBH for an individual tree using its species, height, local stem density and local stand height. Implementation of the DBH model within TSI builds on this work, adapting individual tree metrics calculated from LiDAR, and adjusted local density (stem/ha).

The DBH model function is as follows.

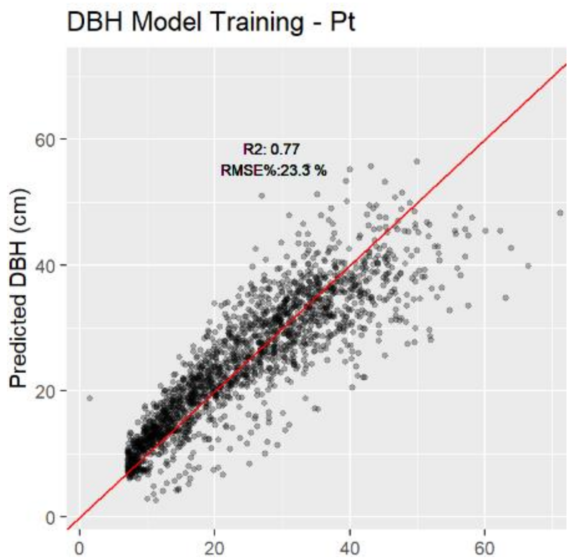
$$\mathrm{DBH} = \mathrm{b}_1(\mathrm{HT} - 1.3)^{\mathrm{b}_2} \exp\left[-\mathrm{b}_3(\mathrm{HT} - 1.3)\right] \times \mathrm{b}_4^{\sqrt{\mathrm{DEN}/1000}} \times \exp\left(\mathrm{b}_5 \mathrm{ST\_HT}\right)$$

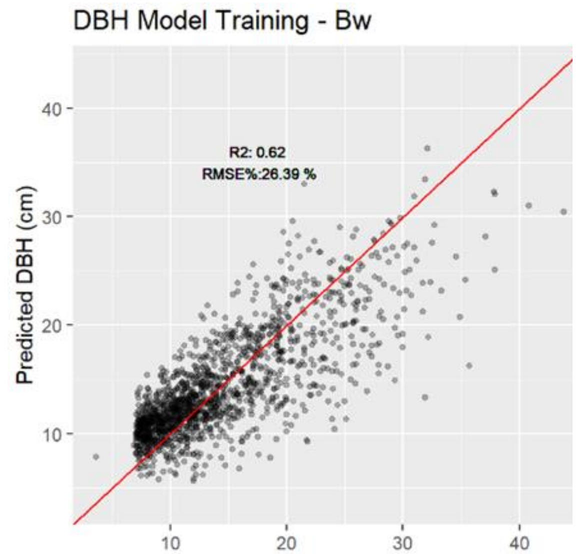
Where DBH is tree diameter (cm) measured at a breast height (i.e. 1.3 m above the ground); HT is individual tree height (m); DEN is stand density (stems/ha for trees taller than 5.0 m) calculated based on 11.28m radius plot around the tree; ST_HT is stand height, calculated as the average height of the all ITI segmented trees that land within 11.28 m radius around the target ITI tree (AVG_TR_HGT); and b_1-b_5 are model parameters (Table 4).

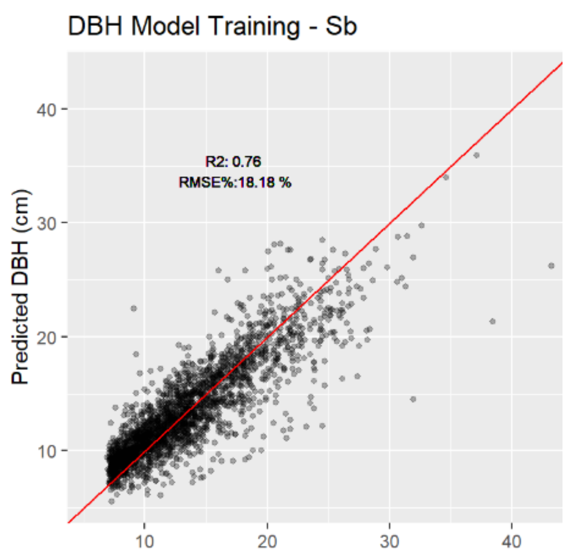
Once DBH has been predicted for each tree, the stump diameter, volume, basal area, and volumes for each stem can be calculated using taper equations.

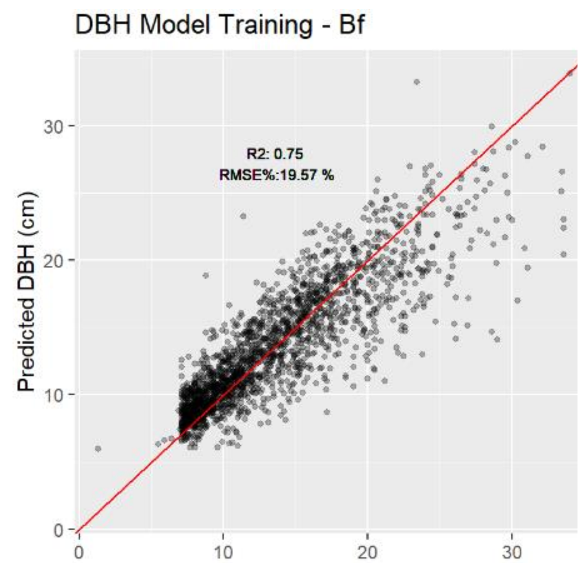
Table 4. Parameter estimates and goodness of fit statistics.

Species	n_total	b_1	b_2	b_3	b_4	b_5	rmse	rmse_pct	r^2
Pt	2183	0.66898	1.54884	-0.00182	0.69394	-0.04370	5.51581	0.22019	0.79101
Bw	1621	4.41580	0.52831	-0.04748	0.64218	-0.02390	3.53746	0.24226	0.68408
Sb	2686	4.82283	0.49013	-0.04077	0.78844	-0.02538	2.31983	0.17130	0.78769
Bf	2314	3.86076	0.44097	-0.03793	0.82332	-0.00317	2.42196	0.17943	0.78925
Pj	1702	4.48420	0.71039	-0.03177	0.73598	-0.04801	3.27954	0.19491	0.74162
Sw	613	4.40994	0.51340	-0.04300	0.84700	-0.02144	3.26576	0.18227	0.84813
Cw	174	5.24492	0.30000	-0.08966	0.73634	-0.00487	2.77911	0.18413	0.81942
La	101	4.51428	0.30000	-0.06872	1.03447	-0.03923	3.26225	0.18858	0.81429


DBH Model Training - Pt
Predicted DBH (cm)
R2: 0.77
RMSE%:23.3 %
0
20
40
60


DBH Model Training - Bw
Predicted DBH (cm)
R2: 0.62
RMSE%:26.39 %
10
20
30
40


DBH Model Training - Sb
Predicted DBH (cm)
R2: 0.76
RMSE%:18.18 %
10
20
30
40


DBH Model Training - Bf
Predicted DBH (cm)
R2: 0.75
RMSE%:19.57 %
0
10
20
30

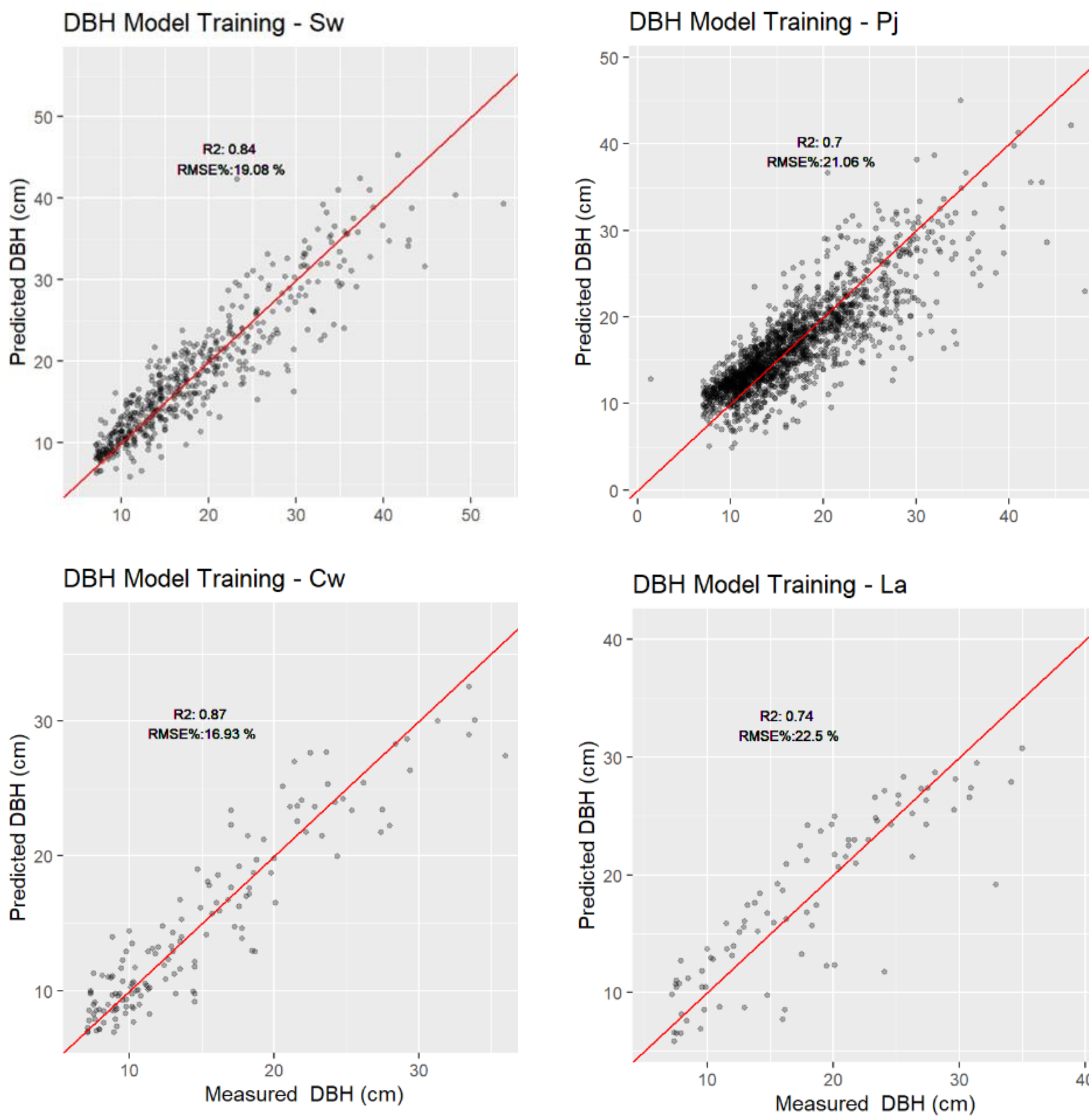


Figure 6. Measured DBH vs Predicted DBH.

3.1.6 Volume and Other Calculations

The volume of each tree is calculated using the functions and methodologies documented in Section 4.7 of Penner, 2020. Zakrzewski's taper model (Zakrzewski and Penner 2013[3]) was used for most species. For plantation jack pine and black spruce, the taper model of Sharma and Parton[4] (2009) was used. Both the gross volume and gross merchantable volume within each tree (the volume of a stem between the stump height and a minimum top diameter) are calculated using the utilization standards summarized in Table 5.

Table 5. Utilization standards table adapted from MIST.

Species	Minimum Top Diameter Inside Bark Scaling Manual
White birch, poplar	14cm
Other hardwood	18cm
White & red pine, hemlock	14cm
Other conifers	10cm

Net merchantable volumes were calculated as gross merch * decay/waste/breakage using species specific factors.

Basal Area

Basal area (m^2/ha) is a function of tree diameter and is an important stand level attribute. Basal area for each individual tree (m^2) is simply the area of cross sectional area of the tree at DBH, calculated as:

$$\text{Using DBH in cm's:} \quad BA\,(m^2) = \pi \times (DBH/200)^2$$

Biomass

Biomass (oven dry weight kg) for each tree is calculated based on the gross stem volume (m^3) multiplied by expansion factors for bark, roots, branches and foliage. This is then multiplied by the density (oven dry weight (kg)/green volume (m^3)) of each species (Miles and Smith 2009).

3.1.7 Estimated Tree Age

The age of each stem is estimated using species, height, and site index value from the previous FRI as inputs into the MIST functions. As the predicted ages rely heavily on the historic FRI site index, some ages returned will be erroneous and should only be used as an approximate guideline.

[3] Zakrzewski, W.T and M. Penner. 2013. A comparison of tree stem taper models for use in Ontario. Ont. For. Res. 10 Inst., Queen's Printer for Ontario. Forest Research Report No. 176. 26p.

[4] Sharma, M., and J. Parton. 2009. Modeling stand density effects on taper for jack pine and black spruce plantations 38 using dimensional analysis. For. Sci. 55(3):268-282

3.2 HEXAGON AREA-BASED INVENTORY

The first step of the Hexagon Inventory process is the aggregation, or rolling up, of the ITI data into 400 m^2 hexagon cells. These base ITI metrics are then treated as predictor variables, along with a range of other ABA metrics, to estimate the final attributes on each hex tile using regressions built from the ground plot data. Estimates of volume, basal area and stems per hectare are created for each hexagon tile.

For the total stem per hectare adjustment model, a total of 202 plots were used to create the model. 75 out of 202 plots are within the 100,000 ha subset project area and have ITI segmented. For volume, basal area, and merchantable stem per hectare adjustment models, only the 75 plots with the AOI were used to create the models.

ITI attributes in a hexagon are adjusted only when the number of stems per hexagon is greater than or equal to ten (10), or greater than or equal to 250 stems per hectare. Furthermore, merchantable attributes are only modified when the number of merchantable stems is greater than or equal to ten (10) per hexagon. The assumption is that if the number of stems is low (9 or less), it is very likely that the ITI process is capturing all the trees in that cell and the summed ITI volumes will be more accurate than ABA predicted volumes.

The following steps describe the Hexagon Inventory process in greater detail.

3.2.1 Species Proportions

The species of each tree is predicted during the ITI process and is carried forward for use in the Hexagon Inventory. Species proportions were not corrected or modified when rolling up to the hexagon cells and are projected over the adjusted tree list as an area-based attribute. Species percentage is calculated as the percentage of basal area as estimated by ITI excluding dead trees.

3.2.2 Stems Per Hectare Adjustment

Initial SPH estimates from the ITI inventory may under predict actual SPH since segmentation is known to miss trees, especially in dense conifer stands. It is critical to get a good estimate of stem counts so that accurate piece size values can be calculated. The final SPH estimate was created using the following regression:

Total Stems Per Hectare

$$SPH1 = b_1 SPH2^{b2} MaxHeight^{b3}$$

Where:

b_1 = 5.0779, b_2 = 0.8773. b_3 = -0.1394
SPH1 = Field plot total density for all trees (stems/ha)
SPH2 = ITI plot total density for all trees (stems/ha)
MaxHeight = Maximum height of all ITI trees within 11.28 m plot

Model fitting statistics are: R^2 = 0.55, and RMSE = 467 stems/ha for the training sample set.

Figure 7 shows the modelling data (left) and the comparison between observed and predicted total densities (right).

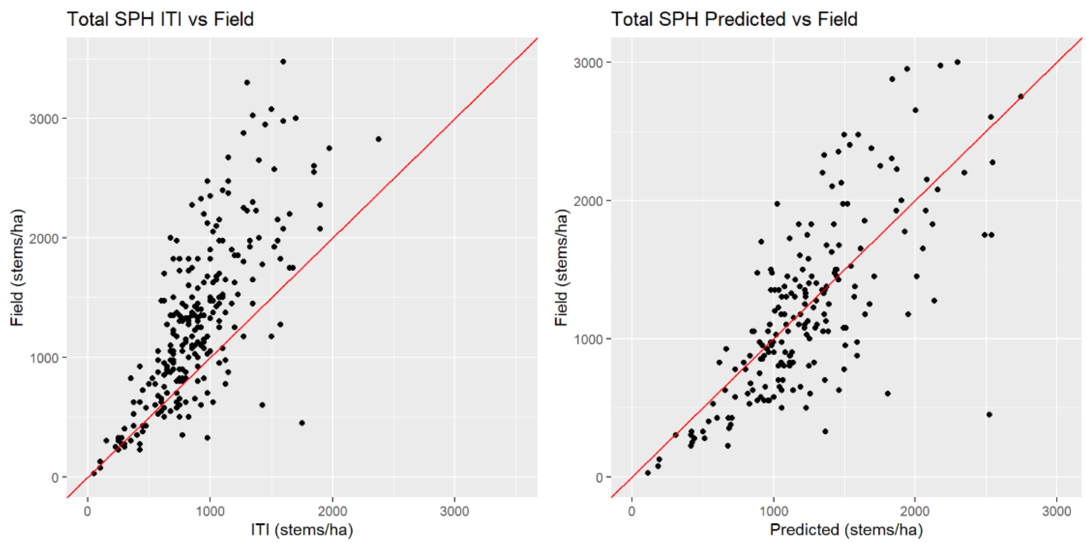


Figure 7. Field vs ITI total stems per hectare (left) and field vs predicted total stems per hectare (right).

Merchantable Stems Per Hectare

$$SPH1 = b_1 SPH2^{b2}$$

Where:

$b_1 = 3.5839$, $b_2 = 0.8645$

SPH1 = Field plot total density for merchantable trees (stems/ha)

SPH2 = ITI plot total density for merchantable trees (stems/ha)

MaxHeight = Maximum height of all ITI trees within 11.28 m plot

Model fitting statistics are: $R^2 = 0.71$, and RMSE = 284 stems/ha for the training sample set.

Figure 8 shows the modelling data (left) and the comparison between observed and predicted total densities (right).

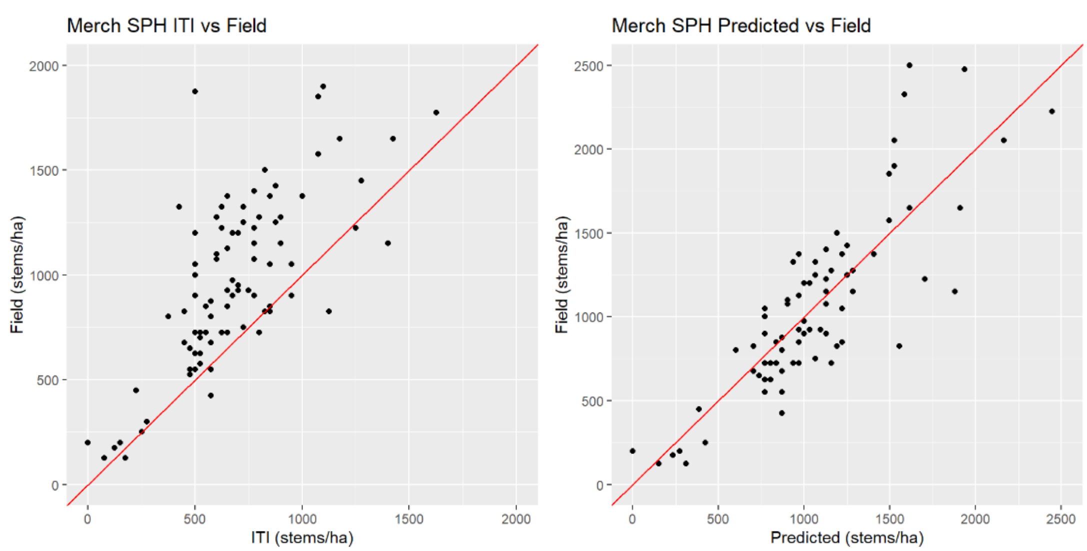


Figure 8. Field vs ITI merchantable stems per hectare (left) and field vs predicted merchantable stems per hectare (right).

3.2.3 Basal Area

Total and merchantable basal areas based on ITI trees are determined for each hexagon, and these serve as predictor variables for the final BA assigned to the hex.

Total Basal Area

$$BA1 = b_1 BA2^{b_2} * exp(-b3 * MaxHeight)$$

Where:

b_1 = 4.8361, b_2 = 0.4601, b_3 = 0.0211
BA1 = Field plot total basal area (m^2/ha)
BA2 = ITI plot total basal area (m^2/ha)
MaxHeight = Maximum height of all trees within 11.28m plot

Model fitting statistics are: R^2 = 0.65, and RMSE = 8.88 m^2/ha for the Training sample set. Figure 9 shows the modelling data (left) and the comparison between observed and predicted total basal area.

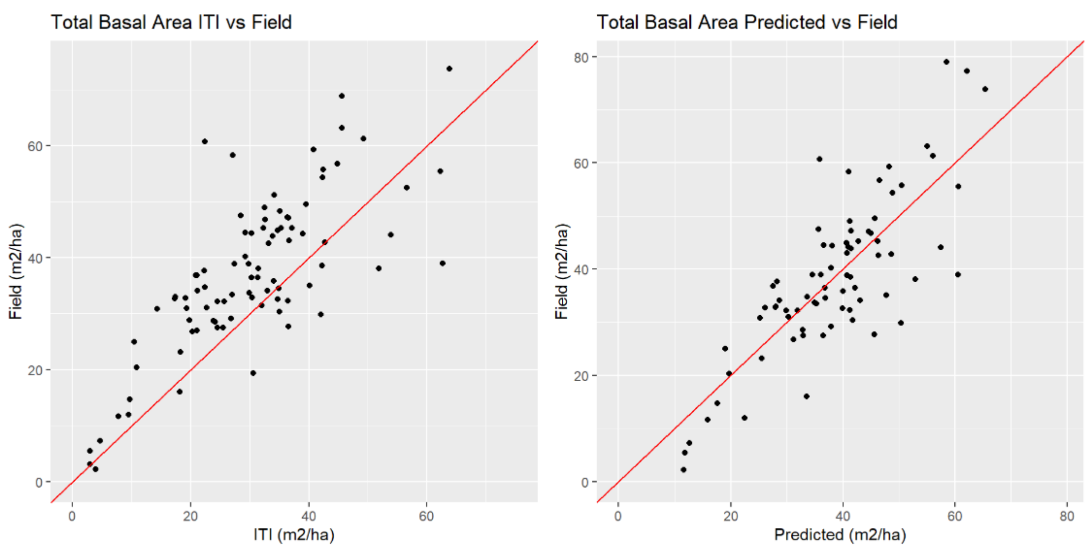


Figure 9. Field vs ITI total basal areas (left) and field vs predicted total basal areas (right).

Merchantable Basal Area

$$BA1 = b_1 BA2^{b_2} * exp(-b3 * MaxHeight)$$

Where:

b_1 = 3.7217, b_2 = 0.4851, b_3 = -0.0264
BA1 = Field plot merch basal area (m^2/ha)
BA2 = ITI plot merch basal area (m^2/ha)
MaxHeight = Maximum height of merchantable trees within 11.28m plot

Model fitting statistics are: $R^2 = 0.7$, and RMSE = 8.72 m^2/ha for the Training sample set. Figure 10**Error! Reference source not found.** shows the modelling data (left) and the comparison between observed and predicted merchantable basal area.

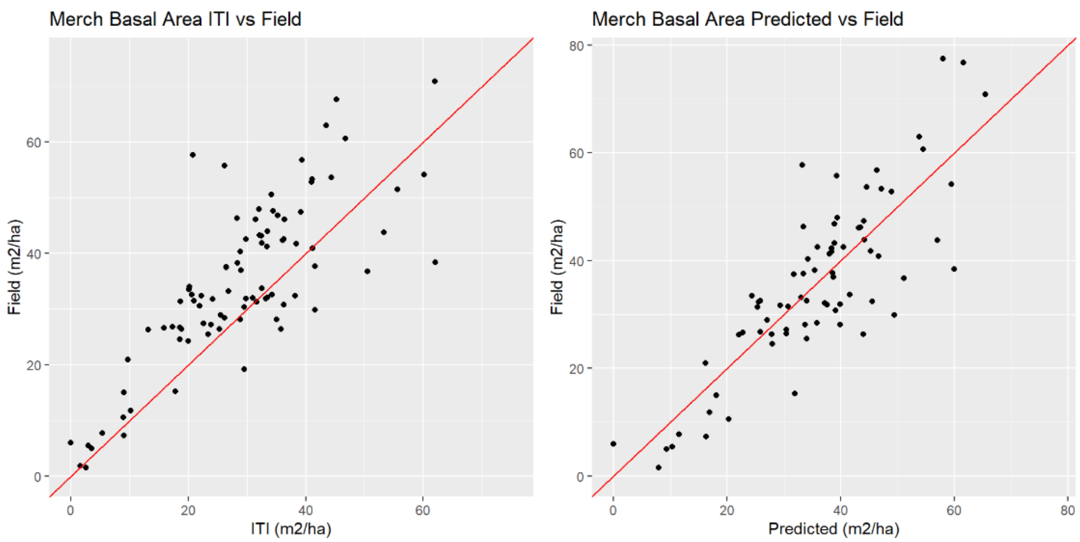


Figure 10. Field vs ITI merchantable basal areas (left) and field vs predicted merchantable basal areas (right).

3.2.4 Volume Adjustment

Gross, gross merchantable, and net merchantable volumes for each ITI stem (described earlier) are summed for each hexagon and can then be used as a predictor variable for the final volume assigned to the hex.

When ITI volumes are aggregated to a plot or block level for a comparison to field data, results are typically biased slightly low since the ITI does not generally identify all stems. The Hex process adjusts aggregated ITI volumes to get unbiased volume estimates.

A standard regression analysis is implemented to predict volumes using the ITI estimate and other area-based LiDAR metrics as predictor variables.

Gross Volume

$$VOL1 = b_1 VOL2^{b_2}\, exp(-b_3 GAP) * MaxHeight^{b4}$$

Where:

$b_1 = 1.3225$, $b_2 = 0.4309$, $b_3 = 2.9173$, $b_4 = 0.9974$
VOL1 = Field gross volume (m^3/ha)
VOL2 = ITI gross volume (m^3/ha), compiled from ITI tree data
GAP = Percentage of CHM pixels < 3 m within hexagon, or 'GAP_FRACTION'
MaxHeight = Maximum height of ITI within 11.28m plot

Model fitting statistics are: $R^2 = 0.8$, and RMSE = 84.32 m^3/ha. Figure 11 shows the modelling data (left) and the comparison between observed and predicted gross merchantable volumes (right).

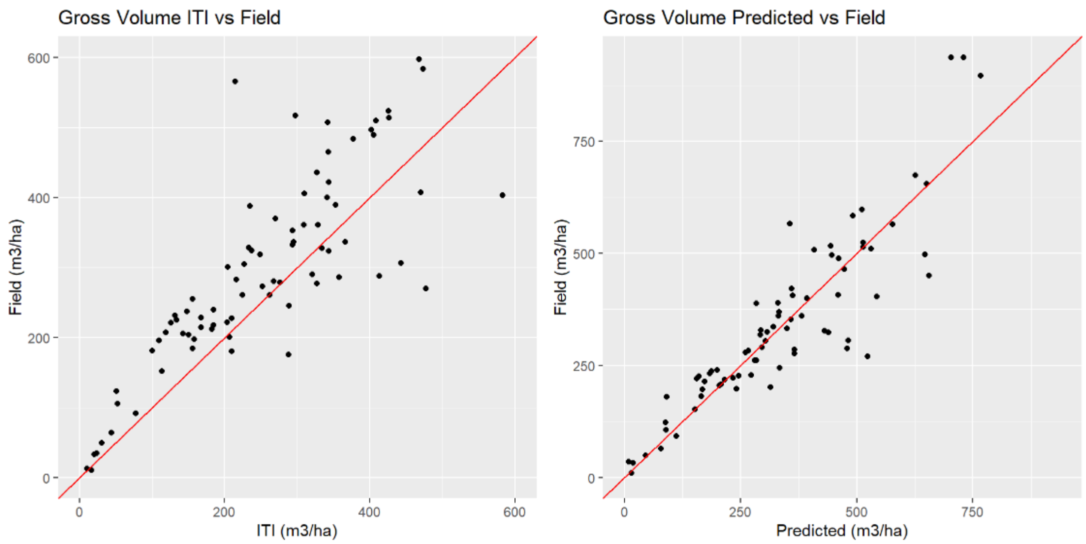


Figure 11. Plots of field vs ITI gross volumes (left) and predicted vs observed gross volumes (right)

Gross Merchantable Volume

$$VOL1 = b_1 VOL2^{b_2}\, exp(-b_3 GAP) * MaxHeight^{b4}$$

Where:

$b_1 = 0.4262$, $b_2 = 0.4325$, $b_3 = 2.5064$, $b_4 = 1.3158$

VOL1 = Field gross merchantable volume (m^3/ha)

VOL2 = ITI gross merchantable volume (m^3/ha), compiled from ITI tree data

GAP = Percentage of CHM pixels < 3 m within hexagon, or 'GAP_FRACTION'

MaxHeight = Maximum height of ITI within 11.28m plot

Model fitting statistics are: R^2 = 0.84, and RMSE = 76.32 m^3/ha for the training sample set. Figure 12 shows the modelling data (left) and the comparison between observed and predicted gross merchantable (right).

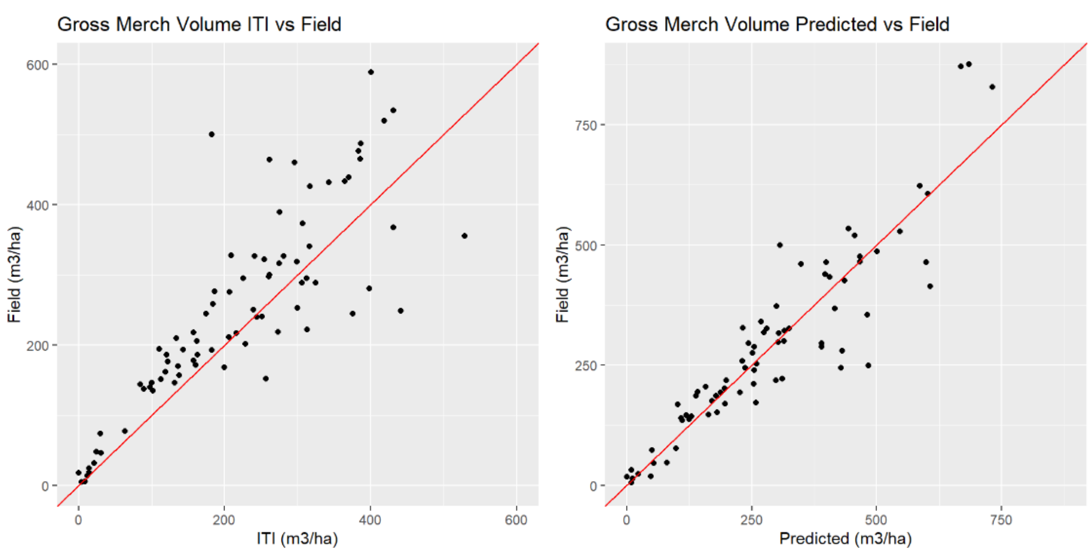


Figure 12. Plots of field vs ITI gross merchantable volumes (left) and predicted vs observed gross merchantable volumes (right)

Net Merchantable Volume

$$VOL1 = b_1 VOL2^{b_2} \, exp(-b_3 GAP) * MaxHeight^{b4}$$

Where:

$b_1 = 0.5480$, $b_2 = 0.3829$, $b_3 = 2.4525$, $b_4 = 1.3092$
VOL1 = Field net merchantable volume (m^3/ha)
VOL2 = ITI net merchantable volume (m^3/ha), compiled from ITI tree data
GAP = Percentage of CHM pixels < 3 m within hexagon, or 'GAP_FRACTION'
MaxHeight = Maximum height of ITI within 11.28m plot

Model fitting statistics are: R^2 = 0.81, and RMSE = 72.06 m^3/ha for the training sample set. Figure 13 shows the modelling data (left) and the comparison between observed and predicted gross merchantable (right).

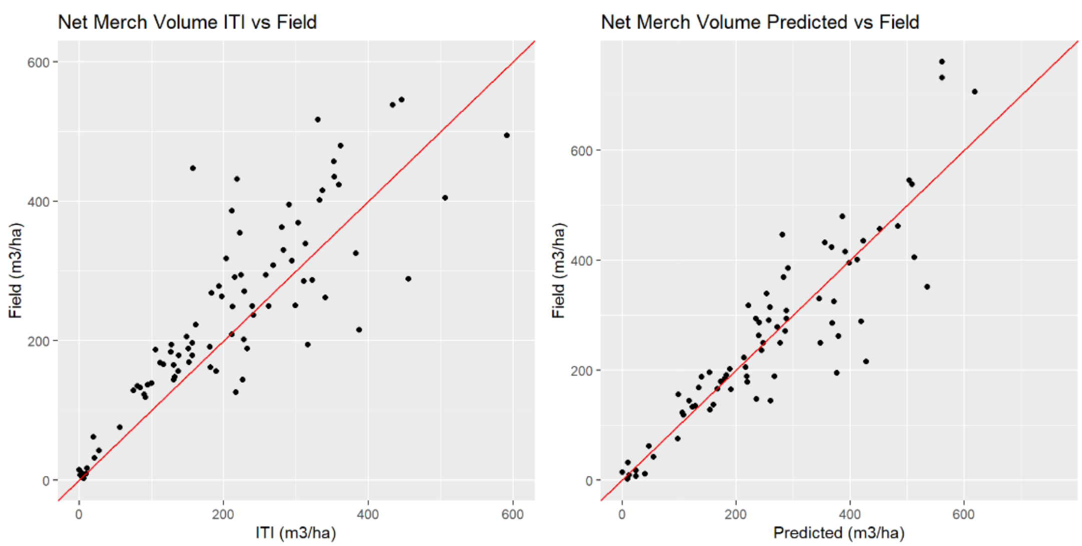


Figure 13. Plots of field vs ITI net merchantable volumes (left) and predicted vs observed net merchantable volumes (right)

3.2.5 Quadratic Mean Diameter

Quadratic mean diameter is calculated using each Hex's merchantable stems/ha and merchantable basal area:

$$QMD = \sqrt{\frac{BA\_MERCH}{0.0000785 \times SPH\_MERCH}}$$

Where:

QMD = Quadratic mean diameter (cm) of merchantable trees
BA_MERCH = Adjusted merchantable basal area (m^2/ha)
SPH_MERCH = Adjusted merchantable stems/ha

3.2.6 Heights

Several different heights are calculated for each hexagon. The top height for each hexagon is determined as the tallest four (4) trees in the hexagon from the ITI data, and the Lorey's height for each hexagon is calculated as the average of all trees weighted by basal area. Figure 14 compares the field vs ITI maximum heights (left) and field vs. ITI top heights (right).

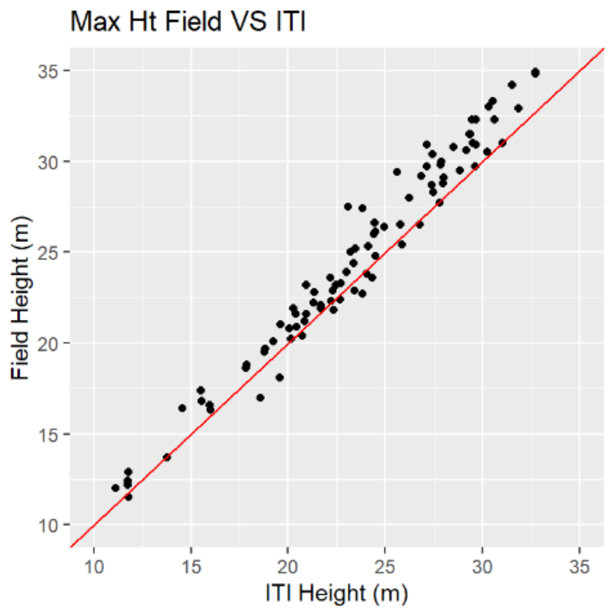


Figure 14. Plots of field vs TSI maximum heights (left), and field vs TSI top heights (right).

3.2.7 Summary of Hybrid Hexagon Approach

- Species proportions are unchanged from initial ITI process;
- Volumes predicted using regression analysis (ITI estimate used as input variable);
- Stems predicted using regression analysis (ITI estimate used as input variable);
- Basal area predicted using regression analysis (ITI estimate used as input variable);
- Max and top heights determined using stems from ITI process; and
- Quadratic mean diameter derived from adjusted stem counts and adjusted merchantable basal area.

3.3 POLYGONAL INVENTORY

The primary goal of the LiDAR derived polygon inventory is to produce homogenous polygons with FRI-like inventory attributes suitable for strategic planning purposes including timber supply analysis. The intent is for this inventory to be a proof of concept for how a new polygon inventory could be created from LiDAR without the need for wall-to-wall photo interpretation as was commonly done in the past.

The FRI-like polygon deliverable has a flat database structure as a feature class in a geodatabase similar in format to what would be downloaded or sourced from the provincial data warehouse. The attribute structure of the polygon inventory is based mostly on the proposed T2 FRI structure with some additional attributes. Using this format will enable users to start using the deliverable immediately for the timber supply process.

3.3.1 Polygon Auto-Delineation

Polygons for the FRI-like inventory were auto-delineated using Trimble's eCognition software. The final dataset also incorporated stereo delineated non-forested and non-vegetated polygons extracted from the existing 2005 Romeo Malette polygon inventory and new waterbody polygons that were extracted from the 2018 LiDAR inventory by the vendor.

First steps included setting the waterbodies and stereo delineated non forest area polygon linework as 'hard lines', so as not to be modified during the eCognition stand polygon segmentation process. No attempt was made to incorporate recent depletions or past silviculture linework, this was done intentionally to explore how a completely automated process would segment stands based on the LiDAR derived variables provided to the software.

The Trimble eCognition software used internal algorithms to develop similarities between neighbouring raster cells based on three input raster variables. The algorithm looks to grow regions (stands) with similar values for leading species (derived from our individual tree inventory), tree heights, and crown closure.

3.3.2 Stand Attribution

The finalized polygons were attributed using the HEX and ITI data as follows:

1.	Species Proportions:	Summary of ITI Species weighted by BA
2.	Basal Area (total, merch):	Area Weighted Avg of Hex Values
3.	Volumes (gross, gross merch, net merch):	Area Weighted Avg of Hex Values
4.	Stems per Hectare:	Area Weighted Avg of Hex Values
5.	Heights (top, Lorey)	Area Weighted Avg of Hex / ITI Values / LEFI (Top Height)
6.	Quadratic Mean Diameter (merch):	Area Weighted Avg of Hex Values

Site index and stand age are key attributes of a forest inventory. It is assumed that stand ages from previous FRI inventories are more reliable attributes than previously interpreted site index values. Historical interpreted ages from FRI were used to update polygon age, then the function from MIST package was used to update Site Index using updated LiDAR heights and dominant species.

Accurate species composition, basal area, volume, heights, stem density and diameter at breast height were the main focus of this project, attributes that were the focus of other FFT-KTTD projects were not considered including: vertical structure and site index.

3.3.3 Comparisons To Traditional FRI

To evaluate the auto delineated polygon inventory, a 2,500-hectare area was assessed by Andy Purton, a highly skilled photo interpreter at Sumac Geomatics. Andy reviewed the inventory with two specific focus areas in mind; quality of the LiDAR derived species composition call and quality of the auto delineated stand polygons.

3.3.3.1 STAND POLYGON DELINEATION

Stand polygon auto delineation is challenging when trying to mimic the results of human photo interpretation. Traditionally, stand polygons are drawn based on similar characteristics in ecosite, tree species and landforms that can be distinguished by the photo interpreter. For this project, LiDAR derived auto delineated stands are created based on similar characteristics of tree species, height, and crown closure (See figures below). Differences in the inputs lead to challenges in effectively comparing the two methods of stand polygon generation.

Figure 15. Example of auto delineated polygons over imagery

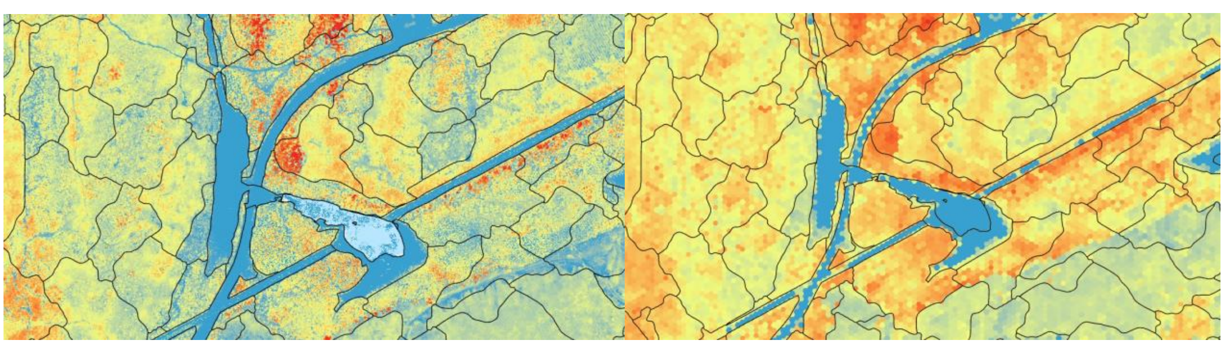


Figure 16. Example of auto delineated polygons over 1m CHM (left) and 400m^2 Hexs (right)

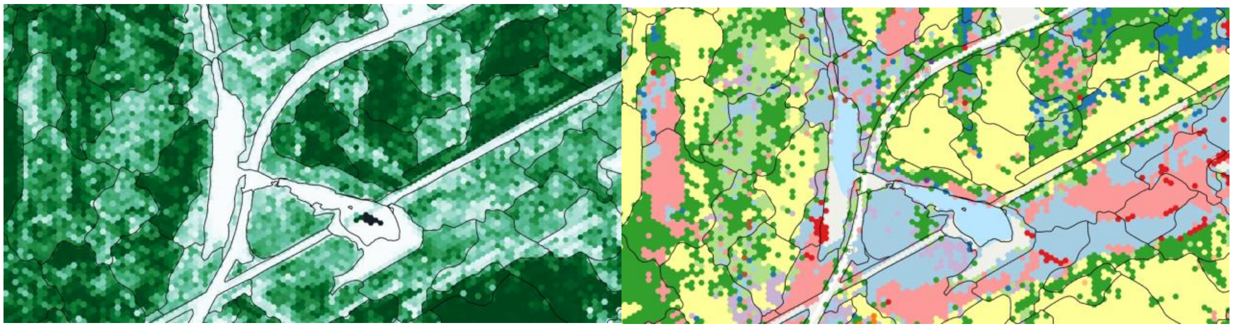


Figure 17. Example of auto delineated polygons over Hex Crown Cover (left) and Hex Leading Species (right).

Generally, the photo interpreter review of the auto delineated stand polygons revealed that the polygons are on average smaller and more compact than photo interpreted polygons and struggled to capture long, thin landform features. The auto delineated polygons often missed hard breaks between species, ecosites and age classes and as a result ended up with complex mixed species compositions and fewer pure stand conditions. Many of the shortcomings identified are a result of the auto delineation process being done on rasters and a need for a post processing smoothing steps that often obscured the hard boundaries captured by photo interpreters. Additional work is required on the polygon generation stage of inventory creation.

3.3.3.1.1 Polygon Size

Table 6 below provides a comparison of the 2005 photo interpreted and 2023 segmentation polygon inventories and the average of forested polygon size. The segmented polygons are on average 58% smaller with an average size of 4 ha and have much less variability in size.

Table 6. Forested polygon size comparison.

Attribute	2005 FRI	2023 Polygon Segmentation	Difference
Number of polygons (FOR)	12,095	20,757	8,662
Minimum (Ha)	0	0	(0)
Maximum (Ha)	145	40	(104)
Mean (Ha)	7	4	(3)
Median (Ha)	4	3	(1)
Standard Deviation (Ha)	10	4	(7)
Variance (Ha)	106	13	(93)

3.3.3.1.2 Polygon Shape

As shown in Figure 18, visually, there are noticeable differences in the shape of the polygon forest stands delineated by photo interpretation when compared to the segmented polygons produced in eCognition. A number of metrics were calculated to quantify the differences and similarities between these two polygon dataset. The perimeter/ area (edge) ratio statistics (Table 7) and distributions (Figure 19) as well as the linearity index statistics (Table 8) and distributions (Figure 20) are very similar. A comparison of the statistics (Table 9) and distributions (Figure 21) of the thinness ratio show some separability between the datasets. The lower average thinness ratio for the photo interpreted inventory is a function of the longer, thinner and irregular forest stand shapes commonly drawn by interpreters. Whereas the higher thinness ratio values of the segmented stands are closer to the geometric attributes of circle. The segmentation tends to create more compact polygons and struggles to capture long, thin polygons that may better represent certain landform and ecosite characteristics on the landscape.

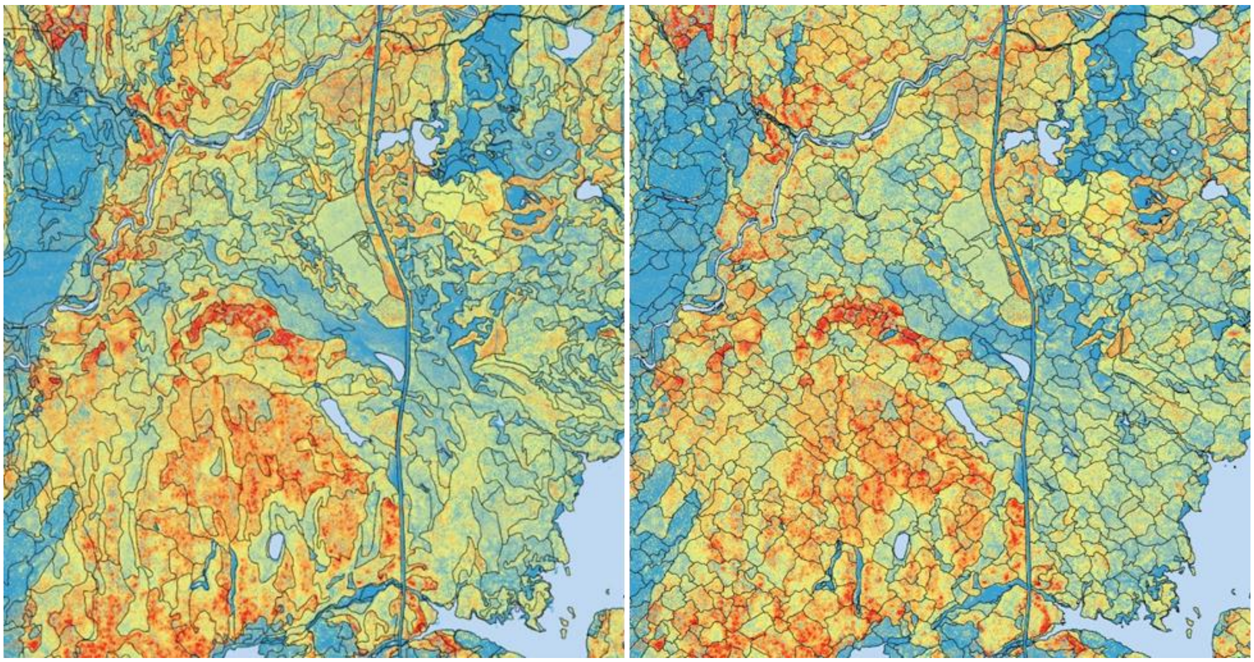


Figure 18. Polygon inventory comparison left: FRI (7 ha), Right: segmentation (4 ha).

Table 7. Perimeter / Area Ratio statistics for FRI and segmented polygon inventories.

Perimeter / Area (Edge) Ratio	2005 FRI	2023 Polygon Segmentation
Number of polygons (FOR)	9,569	18,018
Minimum	0.005	0.007
Maximum	0.212	0.161
Mean	0.030	0.028
Median	0.027	0.025
Standard Deviation	0.014	0.012

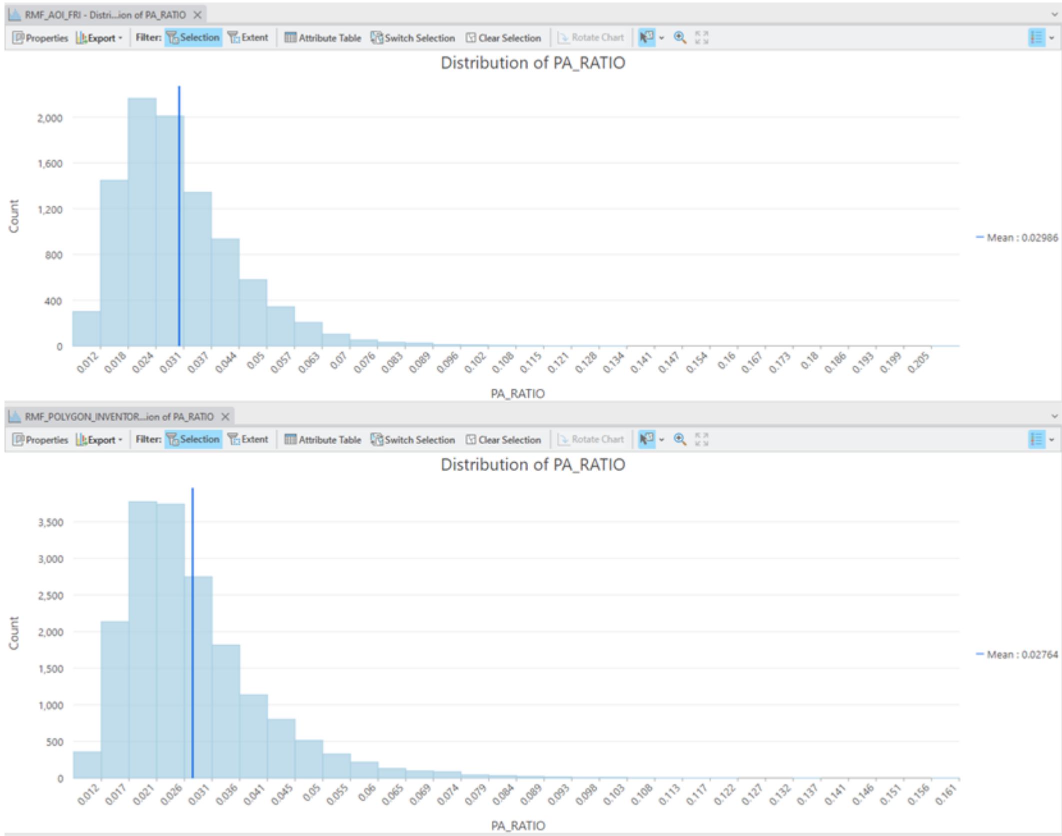


Figure 19. Distribution of Perimeter / Area Ratio for FRI (top) and segmented (bottom) polygon inventories.

Table 8. Linearity index comparison statistics for FRI and segmented polygon inventories.

Linearity Index	2005 FRI	2023 Polygon Segmentation
Number of polygons (FOR)	9,569	18,018
Minimum	0.000	0.000
Maximum	0.986	0.991
Mean	0.210	0.161
Median	0.132	0.089
Standard Deviation	0.218	0.187

Figure 20. Distribution of linearity index for FRI (top) and segmented (bottom) polygon inventories.

Table 9. Thinness ratio comparison statistics for FRI and segmented polygon inventories.

Thinness Ratio	2005 FRI	2023 Polygon Segmentation
Number of polygons (FOR)	9,569	18,018
Minimum	0.015	0.047
Maximum	0.922	0.886
Mean	0.344	0.521
Median	0.319	0.539
Standard Deviation	0.166	0.134

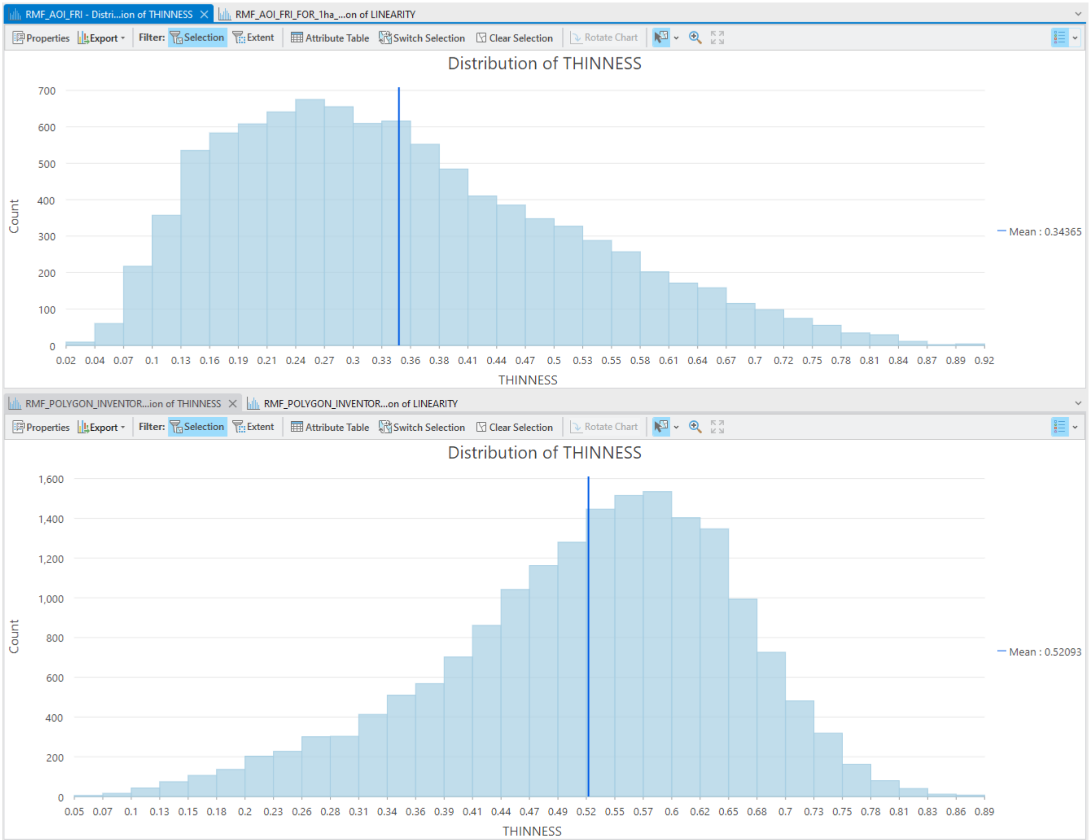


Figure 21. Distribution of thinness ratio for FRI (top) and segmented (bottom) polygon inventories.

3.3.3.2 LIDAR DERIVED SPECIES COMPOSITION

Overall, the assessment of the of the species composition accuracy is that they were well matched with the new polygons and were at least as good as an average photo interpreter. Species compositions were often mixed and included many species as the polygons sometimes struggled to delineate pure stands. Overall, the species are well identified but species composition strings would benefit from better stand polygon delineation.

In addition to differences in delivery format, there are also differences when comparing individual fields collected during a traditional photo interpreted exercise to the LiDAR polygon inventory. As the LiDAR polygon inventory was primarily intended for timber supply analysis, some traditional FRI fields were not populated or captured (e.g, SOURCE, YRSOURCE, DEPTYPE) and some attributes were simply carried forward from the existing 2005 inventory. Administrative fields contain similar data as a traditional FRI, however other fields containing measurable values are calculated using ITI and HEX data in a different manner than a traditional interpreter would use (e.g. species compositions are based on BA not crown closure, multiple height fields are included). Some additional non-traditional fields have been included in the deliverable to facilitate quality assurance by government staff and transparency. This inventory also provides fields not typically found in an FRI dataset (e.g. volumes, stems/ha, basal area,).

4 Deliverables

Inventory deliverables included:

- Documentation
    - ITI_inventory_Database.xlsx – ITI data dictionary. Explanation of deliverable feature class naming conventions.
    - HEXAGON_inventory_Database.xlsx – HEXAGON data dictionary. Explanation of deliverable feature class naming conventions.
    - Polygon_Inventory_Database.xlsx– POLYGON data dictionary. Explanation of deliverable feature class naming conventions.
    - RMF_ITI_HEX_POLYGON_LiDAR_Inventory_Final_Report_2023.pdf – Final report outlining methods, assumptions, approach, various data dictionaries.

- FFT_RMF_HEX_INVENTORY.gdb – HEX (hexagon) inventory. Seamless, area based roll up of ITI data. 1 HEX = 400m^2. Metrics in HEX inventory are summaries of adjusted ITI data using field plots.
    - HEX_INVENTORY – 100,000 ha subset of RMF

- FFT_RMF_ITI_points.gdb – Individual Tree Inventory delivered as point feature classes. Best suited for analysis.
  - A_06 – N_08– delivered as gridded deliverable per FFT_RMF_4km_hexgrid
- FFT_RMF_ITI_poly.gdb – Individual Tree Inventory delivered as polygon feature classes. Best suited for visual use/planning.
    - A_06 – N_08– delivered as gridded deliverable per FFT_RMF_4km_hexgrid
- FFT_RMF_POLYGON_INVENTORY_20230123.gdb
    - RMF_POLYGON_INVENTORY_W_ELC – FRI-like inventory with auto-delineated polygons. Fields populated using 2005 FRI, ITI and HEX outputs.

- FFT_RMF_AOI_GRID.gdb
    - FFT_RMF_4km_hexgrid – 4km grid used for delivery of ITI data
    - FFT_RMF_AOI– Project area of interest as provided by client
    - Individual Tree Inventory

The ITI inventory deliverables are broken into 4 km by 4 km grid cells to ensure manageable data delivery sizes. The grid cell coverage, including the grid cell naming convention, is depicted in Figure 22.

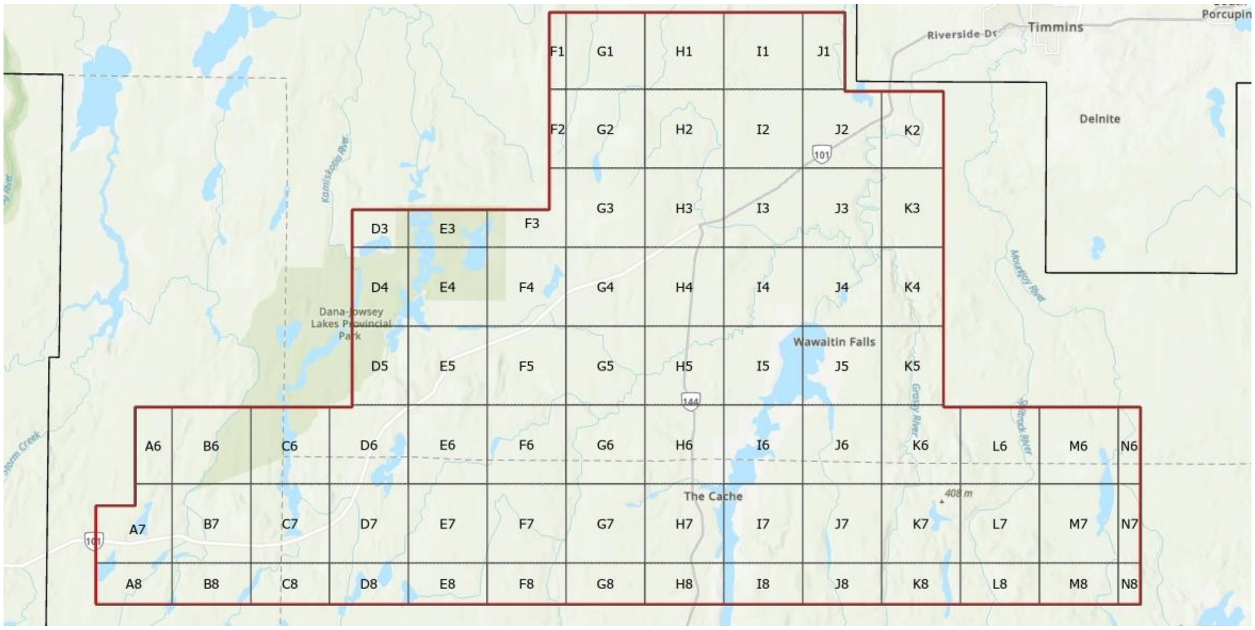


Figure 22. Delivery Grid Extent and Naming Convention.

The grid cell spatial file is located in the '*FFT_RMF_AOI_GRID.gdb*' geodatabase, in the '*FFT_RMF_4km_hexgrid*' feature class.

4.1 INDIVIDUAL TREE INVENTORY (ITI)

The ITI point and polygon deliverables have been grouped into separate ArcGIS geodatabases.

Grid Cell Spatial File

- AOI_GRID
  - FFT_RMF_AOI_GRID.gdb
    - FFT_RMF_4km_hexgrid

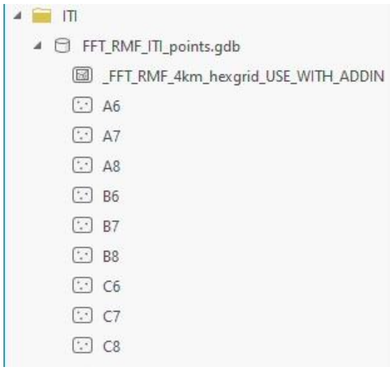
ITI Points and Polygons

- ITI
  - FFT_RMF_ITI_points.gdb
  - FFT_RMF_ITI_poly.gdb

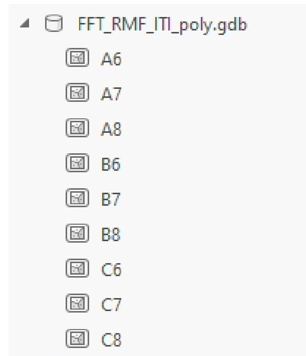
Within each point and polygon geodatabase, each associated polygon or point feature class has been respectively divided and labelled using the grid cells in the '*TFL49_TSI_5km_ExportGrid*' feature class.

For example:

ITI Points



ITI Polygons



4.2 HEXAGON (HYBRID) INVENTORY

Delivered as a single feature class.

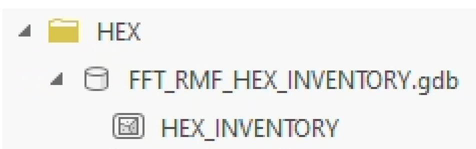


Figure 23. Hexagon Inventory Feature Class Naming Convention

4.3 POLYGON INVENTORY

Delivered as a single feature class.

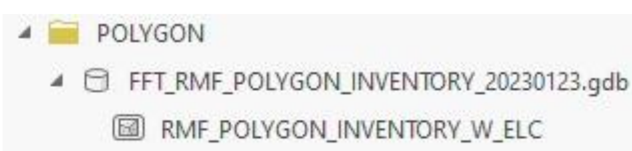


Figure 24: Polygon Inventory Feature Class Naming convention

5 Database Structures and Data Dictionaries

Definitions for the values and assumptions in each field populated in the TSI database are as follows.

5.1 ITI DATABASE STRUCTURE

Field Name	Field Type	Description
OBJECTID	Object ID	Unique feature ID.
HEIGHT	Double	Stem height (m). Measured from ground elevation on DEM to top of tree peak using LiDAR data.
ELEVATION	Double	Average elevation of ground class LiDAR points under the canopy (meters above sea level). If no ground class LiDAR points are found, the elevation at the centroid at the bottom of the tree is used.
SLOPE	Double	Slope of the ground terrain under the crown using DEM (%).
ASPECT	Double	Aspect in bearing degrees of the ground terrain under the crown. (°)
DENSITY	Double	Segmented stems per hectare in associated stand. Stand metric assigned to each segmented stem within a previously delineated polygon, in this case, a historic VRI polygon. (SPH)
LOC_DENSTY	Double	Localized density metric calculated from stems within a 20 m radius of tree point or polygon centroid (SPH).
AVG_TR_HGT	Double	Average tree height
AVGT1PHGT	Double	Top 1% of average tree height of surrounding 11.28m radius
AVGT5PHGT	Double	Top 5% of average tree height of surrounding 11.28m radius
AVGT10PHGT	Double	Top 10% of average tree height of surrounding 11.28m radius
AVG15PHGT	Double	Top 15% of average tree height of surrounding 11.28m radius
AVG20PHGT	Double	Top 20% of average tree height of surrounding 11.28m radius
AVG25PHGT	Double	Top 25% of average tree height of surrounding 11.28m radius
AVGTP4HGT	Double	Average height of 4 tallest trees in surrounding 11.28m radius
CANOPYAREA	Double	Canopy Area of the segmented tree as seen in a planimetric view (m^2). Crown area limited by canopies of neighbouring trees and measured top-down from the top of tree to a maximum of 30% of the tree's height.
CANOPYDIAM	Double	Diameter of tree canopy extent (m).
CANPYRATIO	Double	Uses Canopy Height Model. Ratio of summed pixels 2 m in height within 11.28 m radius from peak point of tree. Proxy for 'local' canopy cover > 2 m.
LV_CPY_PCT	Double	Percentage live crown of the tree. Measured as a decimal ratio value of tree's height.

NM_LDR_PTS	Integer	Number of LiDAR points that intersected segmented stem.
AVG_INT_R1	Integer	Average intensity of first returns in segment
LIDAR_AGE	Double	Age determined using growth curves, site index and height
LIDAR_YR	Integer	Year that LiDAR data was collected.
SITE_INDEX	Double	Site index
POLYID	Text	ID link to 2005 RMF polygon inventory
ECO_ZONE	Text	Ontario Eco Region
ECO_SUBZONE	Text	Ontario Eco District
ECO_VARIAN	Text	Ontario Forest Ecosystem Classification (FEC) Code
UNIQUE_ID	Text	Internal tree ID number concatenated with Grid Cell (HEXID) identifier.
STANDID	Text	ID of the Section containing the tree.
HEXID	Text	Associated 400 m^2 delivery hex cell
GRID_ID	Text	Associated 4 km x 4 km delivery grid cell
PEAK_X	Double	X co-ordinate of peak of tree. This is also the X co-ordinate of the point corresponding to the tree. (Projection = NAD 1983 CSRS UTM Zone 17N)
PEAK_Y	Double	Y co-ordinate of peak of tree. This is also the Y co-ordinate of the point corresponding to the tree. (Projection = NAD 1983 CSRS UTM Zone 17N)
LOW_SPH	Double	Stems Per Hectare value for trees segmented between heights of 5 m and 10 m within an 11.28 m radius of the tree (400 m^2).
MED_SPH	Double	Stems Per Hectare value for trees segmented between heights of 10 m and 20 m within an 11.28 m radius of the tree (400 m^2).
HIGH_SPH	Double	Stems Per Hectare value for trees segmented above 20 m height within an 11.28 m radius of the tree (400 m^2).
VT_CON_PCT	Double	Vertical Connectivity. Percentage of 0.5 m bins up the height of the tree that have points in them. Low values (< 0.5) have lidar points concentrated higher in the segmentation, high values (0.5 to 1.0) have las points spread throughout the height of the segmentation.
SPECIES	Text	Species of tree as predicted by TSI models and processes. Codes assigned as per Ontario tree species
SP_RANKING	Text	Ranks the three most probable species codes per TSI analysis.
SP_PROB_1	Double	TSI determined probability that the species indicated in the first position of “SP_RANKING” is correct. (%)
SP_PROB_2	Double	TSI determined probability that the species indicated in the second position of “SP_RANKING” is correct. (%)
SP_PROB_3	Double	TSI determined probability that the species indicated in the third position of “SP_RANKING” is correct. (%)
GROSS_VOL	Double	Gross volume of tree (m^3) including non-merchantable waste from ground height to top of tree. Total Gross Volume is calculated in three parts using IMPLIEDDBH and Kozak’s Taper Equation and Newton’s Volume Formula.

GROSS_MVOL	Double	Gross merchantable volume of tree (m^3) from stump height (bottom) to min. diameter (top). Value equivalent to the total volume from all the attributed "LOG##_VOL"s. Stump Height = 30 cm. Min Top Diameter = 10 cm.
DWB_FACTOR	Double	Decay, Waste and Breakage factor (%). As per VDYP. Function of SPECIES prediction, LIDAR_AGE, BEC_ZONE, and tree dimensions.
NETMERCHVO	Double	Net Merchantable Volume of tree (m^3). Calculated as the "GROSS_MVOL" adjusted for Decay/Waste/Breakage using "DWB_FACTOR".
BIOMASS	Double	Biomass of tree in kilograms (kg).
BASAL_AREA	Double	Basal area of the tree measured at Breast Height (m^2) using "DBH".
DBH	Double	Calculated DBH (cm) outside bark using allometric equations based on "HEIGHT" and "LOC_DENSTY".
NUM_LOGS	Long Integer	Number of logs in segmented stem. Log length = 5.0m. Last log will measure longer than, or equal to, 3.0 m. Any length shorter than 3.0m will be added to previous log length.
STUMP_HGT	Double	Stump height of merchantable stem. (Default set to 30 cm.)
TOP_DIAM	Double	Top diameter of merchantable stem inside bark. (Default set to 10 cm)
LOG01_LEN (Repeated for LOG02 to LOG10)	Double	Length of LOG # (m).
LOG01_BT_D (Repeated for LOG02 to LOG10)	Double	Diameter at bottom of LOG # (cm) inside bark.
LOG01_TP_D (Repeated for LOG02 to LOG10)	Double	Diameter at top of LOG # (cm) inside bark.
LOG01_VOL (Repeated for LOG02 to LOG10)	Double	Gross Merchantable Volume of LOG # (m^3) inside bark. "DWB_FACTOR" not applied.

5.2 HEXAGON (HYBRID) DATABASE STRUCTURE

Field Name	Field Type	Description
OBJECTID	Object ID	Unique feature ID.
HEX_ID	String	Hexagon ID. Cross reference field with ITI database.
PRODGRIDID	String	Unique 250m x 250m LiDAR production grid cell ID.
EXPTGRIDID	String	Unique 5 km x 5 km grid cell id associated with ITI delivery.
LEADING_SPP	String	Species that has largest percentage (live only)
CROWN_CLOSURE	Double	Crown closure associated with stems in Hexagon. Uses CHM and TOP_HEIGHT. (%)
GROSS_VOL_PRED_HA	Double	Gross total volume per hectare. Value adjusted using regression models. (m3/ha)

GROSS_MVOL_PRED_HA	Double	Gross merchantable volume per hectare. Value adjusted using regression models. (m3/ha)
NET_MVOL_PRED_HA	Double	Net merchantable volume per hectare. Value adjusted using regression models. (m3/ha)
DWB_FACTOR	Double	Average Decay-Waste-Breakage factor. Also calculated as (1-(NET_MVOL_PRED_HA/GROSS_MVOL_PRED_HA))
SPH_GT_5	Integer	Stems Per Hectare greater than 5m
SPH_MERCH	Integer	Merchantable Stems Per Hectare
BASAL_AREA_HA	Double	Total Basal Area per hectare (trees greater than 5m)
MERCH_BASAL_AREA_HA	Double	Merchantable Basal Area per hectare. Sum of basal area from ITI merchantable stems. Value adjusted using regression models. (m^2/ha)
LIVE_MERCH_STEMS_PER_HA	Double	Sum of live ITI merchantable stems per hectare. Value adjusted using regression models. (sph)
DEAD_MERCH_STEMS_PER_HA	Double	Sum of dead ITI merchantable stems per hectare. Value adjusted using regression models. (sph)
STAND_PERCENTAGE_DEAD	Double	Percentage of stand dead. gross merch vol*live% (ITI BA)
GROSS_MERCH_VOL_LIVE	Double	Gross Merchantable Volume of live stems (m3/ha).
GROSS_MERCH_VOL_DEAD	Double	Gross Merchantable Volume of dead stems (m3/ha).
AV_DIAM	Double	Average Diameter at breast height of all trees(>5m) with Weibull adjustment
LOREY_HT	Double	Average height of all trees (>5m) weighted by basal area (with Weibull adjustment)
TOP_HEIGHT	Double	Average height of 4 tallest trees
MAX_HT_ITI	Double	Maximum height of ITI segmented trees
QUAD_DIAM_MERCH	Double	Quadratic Mean Diameter of merchantable stems. Calculated using MERCH_BASAL_AREA_HA and LIVE_MERCH_STEMS_PER_HA (cm)
SPECIES_CD_1	String	Leading species within hexagon. Based on percentage of total basal area.
SPECIES_PCT_1	Integer	Percentage of leading species. Calculated as percentage of total basal area. (%)
SPECIES_CD_2	String	Second species within hexagon. Based on percentage of total basal area.
SPECIES_PCT_2	Integer	Percentage of second species. Calculated as percentage of total basal area. (%)
SPECIES_CD_3	String	Third species within hexagon. Based on percentage of total basal area.
SPECIES_PCT_3	Integer	Percentage of third species. Calculated as percentage of total basal area. (%)
SPECIES_CD_4	String	Fourth species within hexagon. Based on percentage of total basal area.
SPECIES_PCT_4	Integer	Percentage of fourth species. Calculated as percentage of total basal area. (%)

SPECIES_CD_5	String	Fifth species within hexagon. Based on percentage of total basal area.
SPECIES_PCT_5	Integer	Percentage of fifth species. Calculated as percentage of total basal area. (%)
SPECIES_CD_6	String	Sixth species within hexagon. Based on percentage of total basal area.
SPECIES_PCT_6	Integer	Percentage of sixth species. Calculated as percentage of total basal area. (%)
AB_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
BW_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
MR_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
PB_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
PT_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
BF_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
CW_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
LA_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
PJ_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
PR_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
PW_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
SB_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
SW_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
SN_MVOL	Integer	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
HT_(i)_(j)_COUNT	Integer	Adjusted tree count from ht i to j
HT_(i)_(j)_DBH	Double	Adjusted avg DBH from ht i to j

5.3 POLYGON DATABASE STRUCTURE

Field Name	Field Type	Description
OBJECTID *	Object ID	Unique feature ID.
POLYTYPE	Text	General landcover type of each polygon
YRSOURCE	Integer	Year of update
SOURCE	Text	Source of inventory update
FORMOD	Text	Productive forest modifier
DEVSTAGE	Text	Stage of development
YRDEP	Integer	Year of last depletion
DEPTYPE	Text	Depletion type
YRORG	Integer	Year of Origin

SWDPCT	Integer	Softwood species percentage
SPCOMP	Text	Species composition
AGE	Integer	Stand age
LEADSPC	Text	Leading species
HT_LOREY	Double	Lorey's Height - average ht of all trees (>5m) weighted by basal area (with Weibull adjustment). Derived from the ITI
HT_TOP	Double	Top height average height of the 4 tallest trees. Derived using LEFI method to account for within polygon height variability
HT_MAX	Double	Height of the tallest tree in the polygon. Derived from the ITI
CCLO	Integer	Crown closure
SI	Double	Site Index
SC	Integer	Site class
PRI_ECO	Text	Primary ecosite
ACCESS1	Text	Accessibility indicator
ACCESS2	Text	Accessibility indicator
MGMTCON1	Text	Management consideration
MGMTCON2	Text	Management consideration
BIOMASS	Double	Total tree biomass
SMR	Double	Soil Moisture Regime
TEXTURE	Double	Soil Texture
SUBSTRATE	Double	Soil substrate
SUBSTRATE_DEPTH	Double	Soil substrate depth
GROSS_VOL_PRED_HA	Double	Gross total volume per hectare. Value adjusted using regression models. (m3/ha)
GROSS_MVOL_PRED_HA	Double	Gross merchantable volume per hectare. Value adjusted using regression models. (m3/ha)
NET_MVOL_PRED_HA	Double	Net merchantable volume per hectare. Value adjusted using regression models. (m3/ha)
DWB_FACTOR	Double	Average Decay-Waste-Breakage factor. Calculated as; 1-((NET_MERCH_VOL_LIVE+NET_MERCH_VOL_DEAD)/GROSS_MERCH_VOL)
SPH_GT_5M	Integer	Stems per hectare greater than 5m
SPH_MERCH	Integer	Merchantable Stems per hectare
BASAL_AREA_HA	Double	Total cross sectional area of live trees at breast height. Weighted average of associated HEX BASAL_AREA_MERCH values.
MERCH_BASAL_AREA_HA	Double	Total cross sectional area of all merchantable live trees at breast height. Weighted average of associated HEX BASAL_AREA_MERCH values.

LIVE_MERCH_STEMS_PER_HA	Integer	Live merchantable stems per hectare. Weighted average of associated HEX LIVE_MERCH_STEMS_PER_HA values.
DEAD_MERCH_STEMS_PER_HA	Integer	Dead merchantable stems per hectare. Weighted average of associated HEX DEAD_MERCH_STEMS_PER_HA values
STAND_PERCENTAGE_DEAD	Double	Percentage of stand dead by basal area (%)
GROSS_MERCH_VOL_LIVE	Double	Gross Merchantable Volume of live stems (m3/ha).
GROSS_MERCH_VOL_DEAD	Double	Gross Merchantable Volume of dead stems (m3/ha).
AV_DIAM	Double	Average Diameter at breast height of all trees(>5m) with Weibull adjustment
LOREY_HT	Double	Average height of all trees (>5m) weighted by basal area (with Weibull adjustment). Derived from the HEX
TOP_HT	Double	Average height of 4 tallest trees. Derived from ITI.
QUAD_DIAM_MERCH	Double	Quadratic Mean Diameter of merchantable stems. Calculated using MERCH_BASAL_AREA_HA and LIVE_MERCH_STEMS_PER_HA (cm)
SPECIES_CD_1	Text	Leading species within polygon. Based on percentage of total basal area of ITI stems within associated POLYGON
SPECIES_PCT_1	Short	Percentage of leading species. Calculated as percentage of total basal area of ITI stems within associated POLYGON. (%)
SPECIES_CD_2	Text	Second species within polygon. Based on percentage of total basal area of ITI stems within associated POLYGON
SPECIES_PCT_2	Short	Percentage of Second species. Calculated as percentage of total basal area of ITI stems within associated POLYGON. (%)
SPECIES_CD_3	Text	Third species within polygon. Based on percentage of total basal area of ITI stems within associated POLYGON
SPECIES_PCT_3	Short	Percentage of Third species. Calculated as percentage of total basal area of ITI stems within associated POLYGON. (%)
SPECIES_CD_4	Text	Fourth species within polygon. Based on percentage of total basal area of ITI stems within associated POLYGON
SPECIES_PCT_4	Short	Percentage of Fourth species. Calculated as percentage of total basal area of ITI stems within associated POLYGON. (%)
SPECIES_CD_5	Text	Fifth species within polygon. Based on percentage of total basal area of ITI stems within associated POLYGON
SPECIES_PCT_5	Short	Percentage of Fifth species. Calculated as percentage of total basal area of ITI stems within associated POLYGON. (%)
SPECIES_CD_6	Text	Sixth species within polygon. Based on percentage of total basal area of ITI stems within associated POLYGON
SPECIES_PCT_6	Short	Percentage of Sixth species. Calculated as percentage of total basal area of ITI stems within associated POLYGON. (%)

SPECIES_CD_7	Text	Seventh species within polygon. Based on percentage of total basal area of ITI stems within associated POLYGON
SPECIES_PCT_7	Short	Percentage of Sixth species. Calculated as percentage of total basal area of ITI stems within associated POLYGON. (%)
SPECIES_CD_8	Text	Eight species within polygon. Based on percentage of total basal area of ITI stems within associated POLYGON
SPECIES_PCT_8	Short	Percentage of Sixth species. Calculated as percentage of total basal area of ITI stems within associated POLYGON. (%)
AB_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
BW_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
MR_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
PB_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
PT_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
BF_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
CW_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
LA_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
PJ_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
PR_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
PW_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
SB_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
SW_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
SN_MVOL	Double	Species volume percentage based on ITI BA*GROSS_MVOL_PRED_HA
LIDAR_YR	Integer	Year of LiDAR acquisition
LiDARHt_Source	Text	Source of the LiDAR height
SDM	Text	Soil Depth Modifier
Eco	Text	Numerical ecosite code predicted based on preliminary DSM results from CFS project
PRI_ECOCalc	Text	Full ecosite code predicted based on preliminary DSM results from CFS project

6 Appendices

6.1 UTILIZATION SPECIFICATIONS

Utilization specifications used for analysis are summarized as below.

	All Species
Stump height (cm)	30 cm
Min DBH (cm)	12.5 cm
Min Top Diameter (cm)	10.0 cm
Min log length (m)	3.0 m
Log length (m)	5.0 m

6.1 ITI SPECIES CODES

Species Code	Species Common Name
AB	Black ash
BF	Balsam fir
BW	White birch
CW	Eastern white cedar
LA	Eastern Larch
MR	Red Maple
PB	Balsam Poplar
PJ	Jack Pine
PR	Red Pine
PW	White Pine
SB	Black Spruce
SN	'Snag' (dead stem)
SW	White Spruce