LiDAR Derived T2 Inventory for the French-Severn Forest

KTTD Project # 20B-2021

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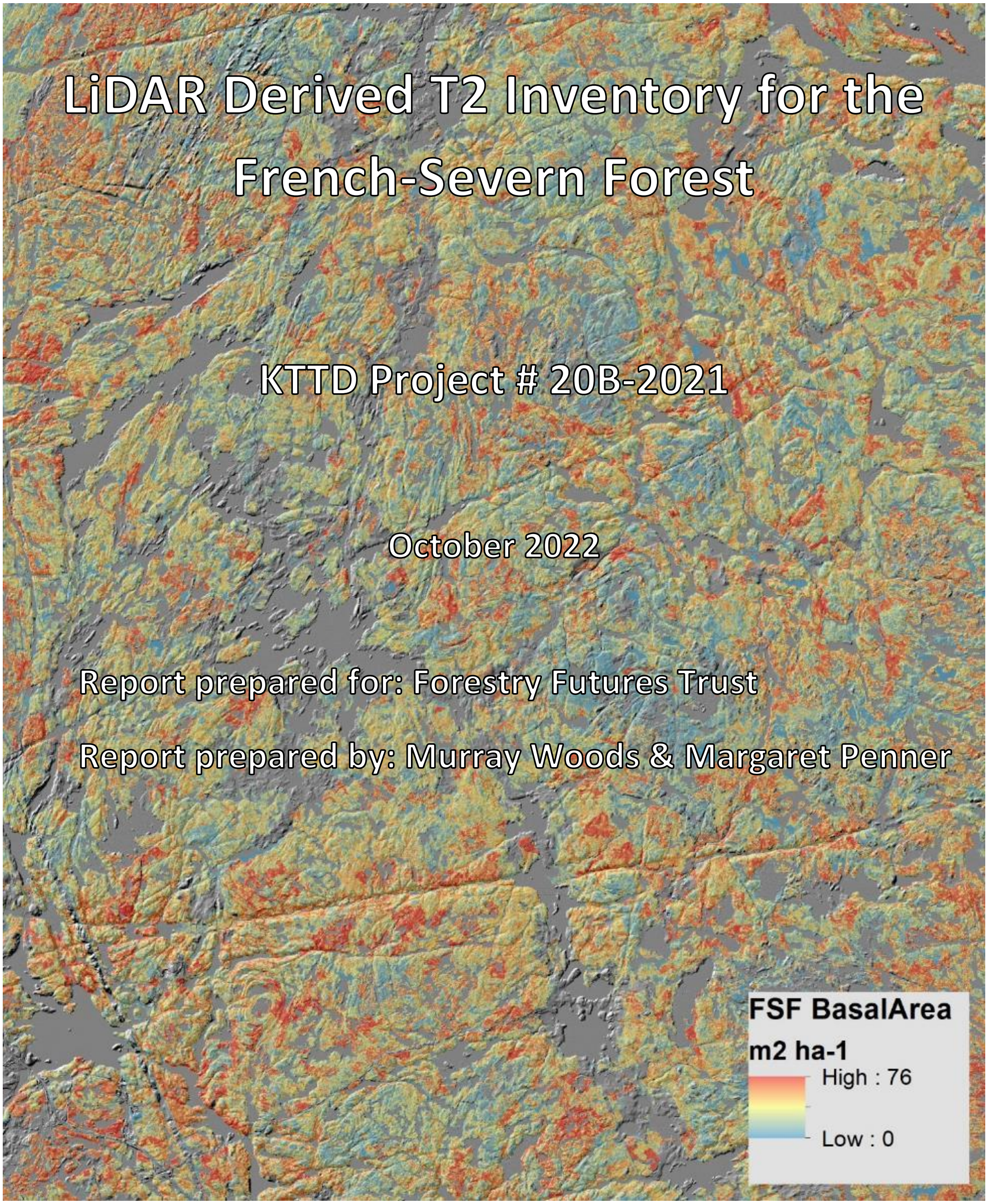


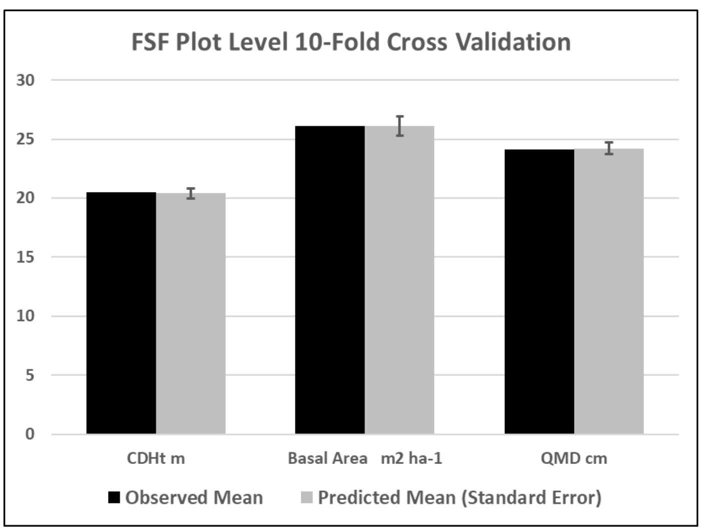
Table of Contents

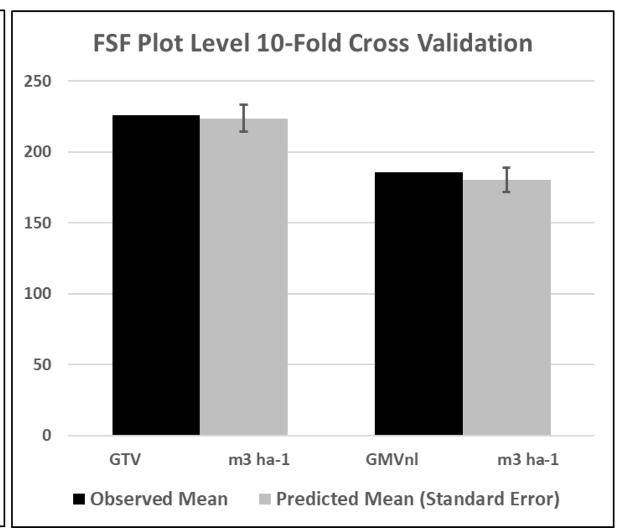
Executive Summary

Single Photon LiDAR (SPL) was acquired over the French-Severn Forest (FSF) during the summer of 2019. A total of 204 LiDAR field calibration plots ($400m^2$ – 11.28m radius) were established on the FSF and measured between June 25, 2020, and September 19, 2020, and an additional 8 Growth and Yield plots measured in September 2021. These plots were used to derive an inventory update ("T2") based on LiDAR models for Height (Dominant/Codominant, Lorey, Top Height), Basal Area (BA), Basal Area merchantable (BAmerch), Volumes (Gross Total (GTV), Gross Merchantable (GMV_NL and GMV_WL)), Quadratic Mean Diameter (QMD), Total Above Ground Biomass (Biomass), Stems, and BA and GMV_NL by four-size classes. Merchantable volume predictions used the provincial scaling specifications for upper diameter limits along with a 30cm stump height. One additional predicted volume raster was produced for the Westwind Forest Stewardship staff for a gross merchantable volume for smaller hardwood upper diameter specifications.

Plot level Model Validation

A 10-Fold Cross Validation (CV) of plot level ($400m^2$) predictions were calculated as a measure of model performance. Root Mean Square Error (RMSE) was calculated on the results of the CV. RMSE is a measure of how close the predictions are to the actual values. The Smaller the RMSE, the better the predictions. RMSE of models for height were 9.7% and 6.9% for Dominant/Codominant and Top height respectively. BA had a 28.9% RMSE while volumes (GTV, GMV_NL, GMV_WL) had 32.6%, 39.0% and 40.5% respectively. QMD reported an RMSE of 22.9% and Biomass 29.6%. Stems resulted in an RMSE of 36.9%. Examples of mean observed and model predictions (along with standard error) of inventory attributes from cross validation are provided below.





The results for the FSF are generally comparable to those reported for the neighbouring Algonquin Park Forest (APF) with slightly higher RMSEs for BA and volume, likely due to fewer calibration plots (FSF n = 190 and APF n = 221).

Stand level Model Validation

Additional validation of the LiDAR predictions for 29 operational cruised stands was conducted. A stand (or harvest block) represents the scale inventory estimates will be used to support management decisions. The validation data was based on Sustainable Forest Licence (SFL) operational prescription development needs in Tolerant Hardwood and Pine stands and did not always cover the full range of stand species/site variability. The operational cruising only surveyed merchantable BA so that attribute is reported here.

For the tolerant hardwood polygons, BA was overestimated by approximately 6% compared to the cruise data while BA was overestimated by approximately 19% for the 6 managed pine stands. It should be emphasized that the cruise data is also an estimate of the polygon BA with 1 prism sweep for every 3 – 4 ha.

Previous studies (White et al. (2021)) have documented the fact that the majority of inventory attribute RMSE's improved at the stand level compared to the CV at the plot scale. Height attributes are not significantly impacted by scale. However, attributes such as ones expressed per area (i.e., basal area, volume) are. Merchantable Basal Area (BAmerch) RMSE for All-Forest types on the FSF was reduced from 30% at the plot scale to 16% at the stand scale (N=29), a substantial improvement. By broad forest type the Pine stands were reduced to an RMSE of 22% (N=6) and the Tolhwd RMSE = 14% (N = 23).

T2 Polygon updating

Raster (20 x 20m) surfaces of the LiDAR predictions were created for the forest polygons. Polygon layers were created from the raster surfaces using the T1 (OPI) polygon layer. The polygon attributes were calculated as the mean of the raster predictions within the polygon **where age $\geq$ 20 years**. Stand level QMD was calculated from polygon BA and Stems. These polygon-based estimates, were used in conjunction with T1 polygon age and species composition to calculate the following additional T2 inventory attributes:

- Site Index
- Stocking
- Cull Fraction
- Net Merchantable Volume (NMV).

Calibration Plot Data Quality

The quality of the field data on the FSF was found to be suspect. **Adjustments to field data measurements is something that should never be required**. However, it was clear that in most cases the field measurements of tree height seem to be higher than LiDAR measurements. Measured heights were adjusted based on LiDAR return information. Unfortunately, it is unknown whether additional measured parameters (DBH, borderline trees, etc.) were also done poorly and their potential impact on the LiDAR model outcomes.

Objective

The objective of this Forestry Futures Trust Knowledge, Transfer & Tool Development (KTTD) project is to develop open source (OS) software code for processing Ontario's Single Photon (SPL) Light Detection and Ranging (LiDAR) and to produce a raster-based product suite and an update for a new T2 polygon Forest Resources Inventory (FRI) for the French Severn Forest (FSF).

Study Site

The French-Severn Forest has a total area (all ownerships) of 1,281,677 ha (
Figure 1) and is located in the Great Lakes - St. Lawrence Forest Region. Crown land classification is broken down as 65% Production Forest, 23% Water, 10% Non-Productive Forest, 1% Other Land (agricultural, unclassified) and 1% Protection Forest.

The dominant forest species communities are tolerant hardwoods and white and red pine types Mixedwoods, Hemlock, Oak, Intolerant Hardwoods, Spruce Fir are more minor components (in the order they are presented) of the FSF. A range of silvicultural systems are employed to ensure a sustainable forest resource into the future. These include single-tree selection, uniform shelterwood and clear cutting. A detailed breakdown of the FSF Forest Units is presented in Figure 2. Additional detailed information about the FSF can be found in the 2019-2019 Forest Management Plan for the French Severn Forest (FMP Online (gov.on.ca)).

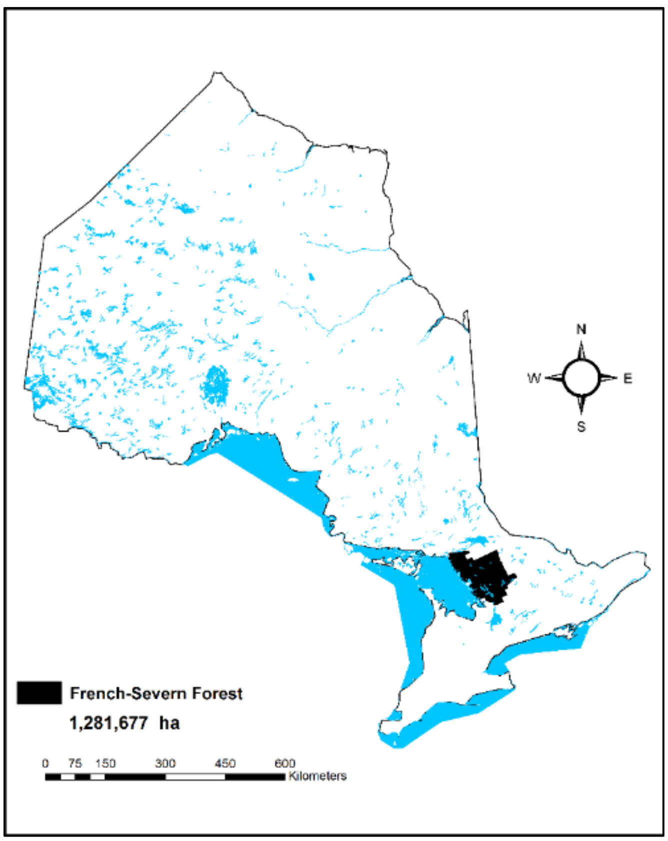


Figure 1 – French-Severn Forest Management Unit Location

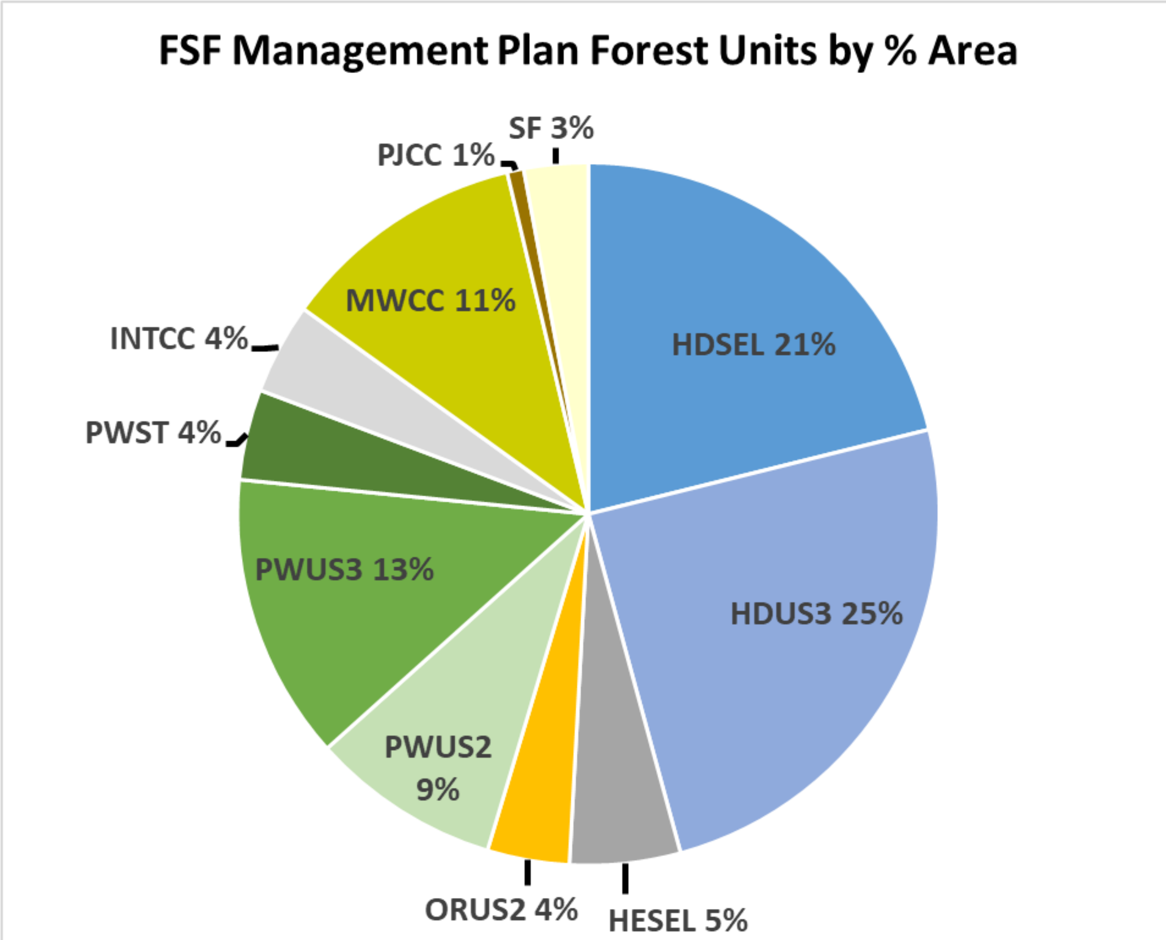


Figure 2 - Percent area by Plan Forest Unit for the FSF.

Data

Airborne LIDAR data

Single Photon LiDAR (SPL) was acquired over the FSF during the summer of 2019. The SPL100 sensor was flown aboard a Piper–PA–31–350 at an average altitude of 3760m. More details of acquisition parameters are provided in Table 1.

Table 1 - LiDAR acquisition specifications for 2019–SPL mission

Parameter	2019 – SPL Description
Pulse repetition rate	6000 KHz
Frequency	21Hz
Scan Angle	+/– 15 Degrees
FOV	30 Degrees
Swath Width	2000m

LiDAR Model Calibration Data

Calibration ground sample measurements followed the province of Ontario's Vegetation Sampling Network Protocol document *(Science and Research Technical Manual TM)*. The Vegetation Sampling Network (VSN) protocol consists of 3 potential plot measurement methodologies. "*A* modules" provide a base set of attributes for all plots. They include a range of stand attributes, tree attributes, and site and substrate attributes. "*B* modules" add in protocols for stem mapping and crown delineations and for assessing a smaller tree and shrub subplot, both of which support LiDAR diagnostics and development. When applied to the permanent subset of VSN plots, the smaller tree and shrub subplot module also supports tracking recruitment and succession. "*C* modules" apply only to the permanent plot subset and add some focus on understory vegetation (understory vegetation subplot) and down woody debris, as well as tree deformities and evidence of wildlife use. The A plot measurement thresholds, common to all protocols, were used to include as many plots as possible in this project.

A total of 212 LiDAR calibration plots ($400m^2$ – 11.28m radius) were established and measured. Most of the plots were established between June 25, 2020, and September 19, 2020 (with a sub-set of 8 Growth and Yield plots being remeasured in September 2021). Calibration plots were selected using a "structurally guided" sampling approach. LiDAR structure measurements for the population were used to determine the full range of structural conditions. Calibration plots were then selected to sample the range of conditions. Where possible, existing provincial permanent sample plots were incorporated into the sampling framework where they met required structural conditions. These plots become the link between ground attributes (i.e., heights, volumes, etc.) and the LiDAR point cloud.

Data Quality

Initial data screening steps quickly identified some field measurement quality issues on the calibration plots established on the FSF. Tree heights measured by the field crew was often found to be higher than the maximum LiDAR return acquired for that plot. There were also some cases where field measured heights were lower than the Lidar returns. In some cases, the differences between the maximum LiDAR return and the measured heights were extreme.

Taking quality height measurements, especially during leaf-on periods of the year on these tall tree species requires extra time and care. Possible reasons for the field measured height issues:

- Some trees were very tall. For accurate height measurement, it is recommended the heights be measured from a distance as least as great as the height.
- In some cases, the canopy cover is dense, particularly in tolerant hardwoods when leaves are on. It may be difficult to see the top of the tree to get a good measurement. It may also be difficult to identify the top of the tree in tolerant hardwoods.
- There were issues with the height measurements. It appears the height measurements corresponded to the height above 1.3m, not the height above the ground. 1.3m was added to every height.

Additional complications and challenges of working with the FSF data set:

- There were no field audits, so data and measurement issues were not identified and corrected.
- There may be GPS errors leading to the field plots not lining up exactly with the LiDAR Point cloud.

Figure 3 provides some examples where field heights were found to exceed, or underestimate recorded maximum LiDAR returns.

- Some plots don't have many ground returns which can impact the LiDAR normalization (this is more likely seen in dense tolerant hardwood plots).
- Sometimes trees lean in or out of the plot.
    - For leaning trees, it's not clear whether the crew measured the height of the tree tip above the ground (which seems to be the field manual procedure) or the length of the bole. No adjustments were made to height based on degree of lean.
- Some plot point clouds contain returns from crowns of trees outside the plot. These trees were not noted as leaning into the plot and therefore, have no mensuration information (Figure 4)

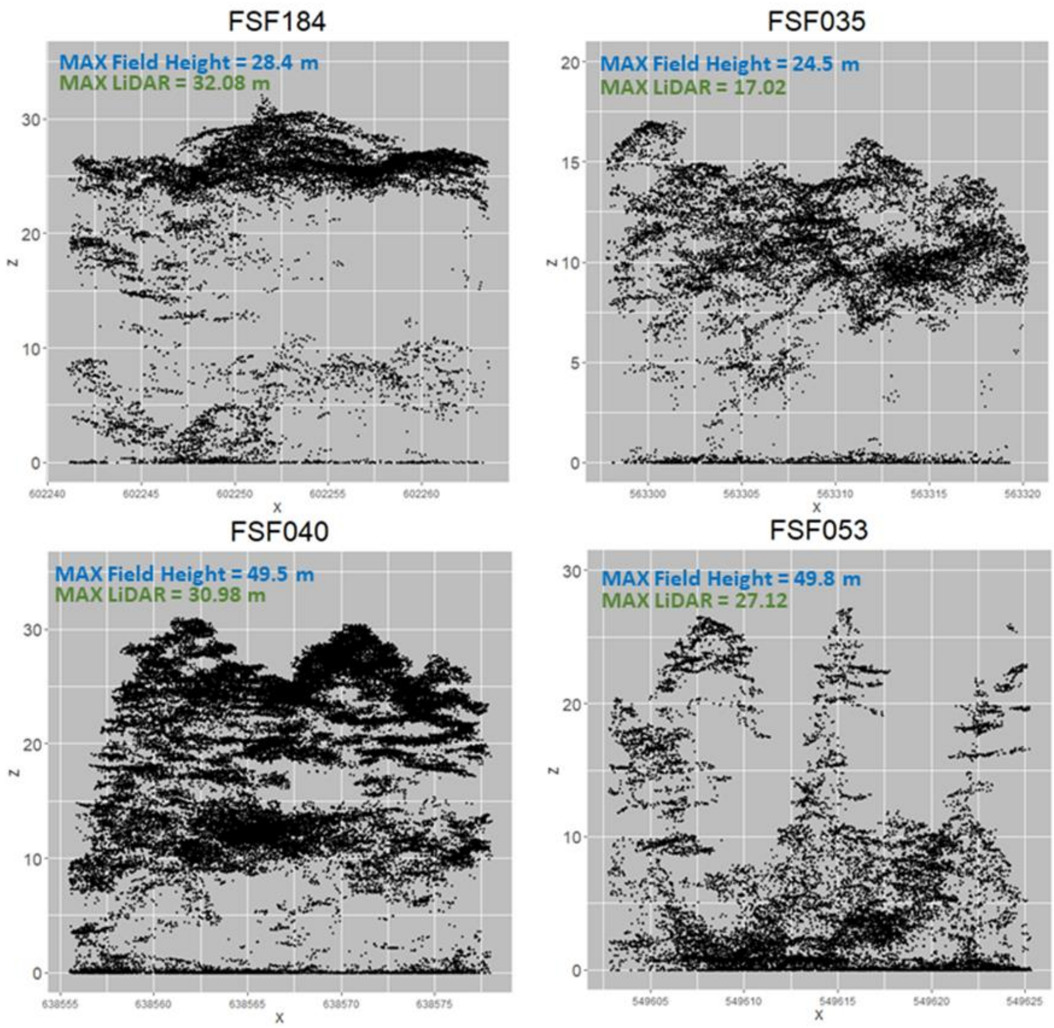


Figure 3 - Examples of Field Height (FH) overestimating or underestimating Maximum LiDAR return.

- Also, in some cases there can be tall dead trees captured in the extracted point cloud (Figure 5). These trees are not included in plot compilation but can impact modeling results.

Figure 6 provides a comparison on maximum LiDAR return versus maximum field height measured on each plot. The 1:1 line indicates identical measurements. It is clearly evident that a significant proportion of calibration plots over-estimated the largest tree height (Figure 6) and the average of the 2 largest field measured heights (Figure 7).

The issues with height measurement quality also raised suspicion on the care undertaken on using the GPS to identify the target plot location, DBH measurement or determination of what trees were within the 11.28m radius plot boundary. Unfortunately, there is no way with the LiDAR returns to evaluate this aspect of field collected data quality.

Calibration Plot Data Adjustment

Adjustments to field data measurements is something that should never be required. However, it was clear that the field measurements seem to be higher than LiDAR measurements. In some rarer cases, field heights were lower than the LiDAR measurements. Possible explanations for these differences have been discussed. It is critical that future field crews understand that the quality of the field data collection impacts the quality of the derived inventory product suite.

However, because tree height has a large impact on the calculation of tree volume, we felt that an adjustment was required for this.

A decision was made (in consultation and approval of MNRF FRI staff) to adjust the field heights using the relationship between the height of the tallest tree on the plot and the maximum LiDAR return. A “plot level ratio" adjustment was made to each plot for the FSF. Where no suitable height trees were available to make a plot level ratio adjustment, the population level adjustment was be used.

Examples of the adjustments to tree heights and the impact on gross total volume are presented in Figure 8 and Figure 9.

Similar issues were encountered on the Algonquin Park Forest (APF) and a similar “correction” applied.

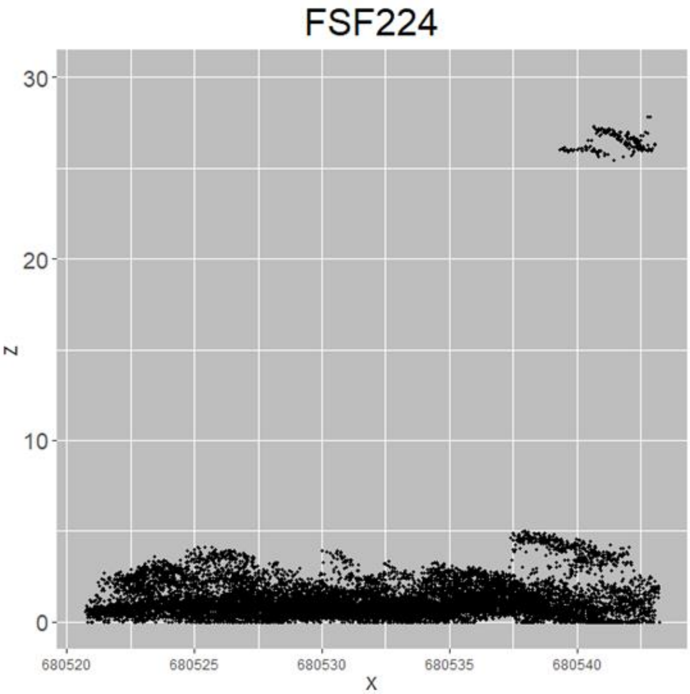


Figure 4 - Example of a plot with crown returns from a tree outside and above the calibration plot.

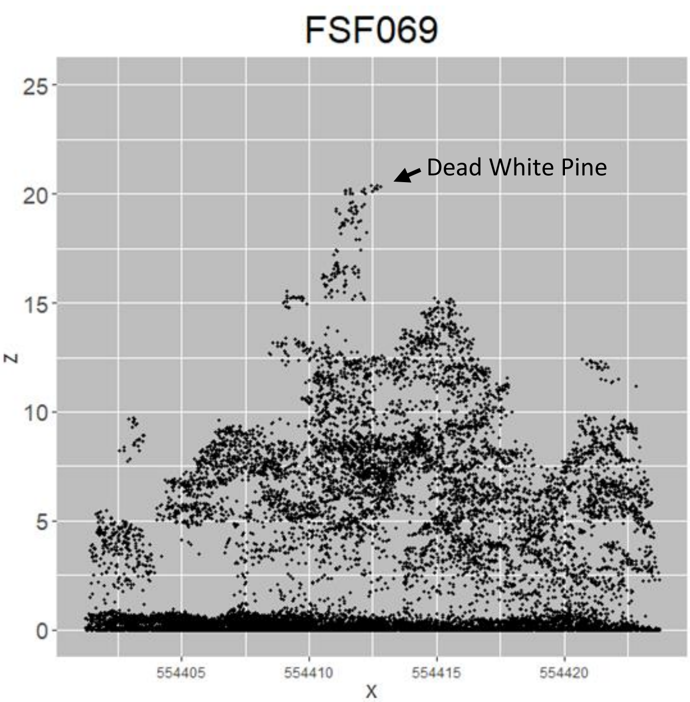


Figure 5 - Example of a tall dead tree capturing LiDAR returns. This tree is not summarized as part of the plot compilation but impacts the model correlations with height-based predictors.

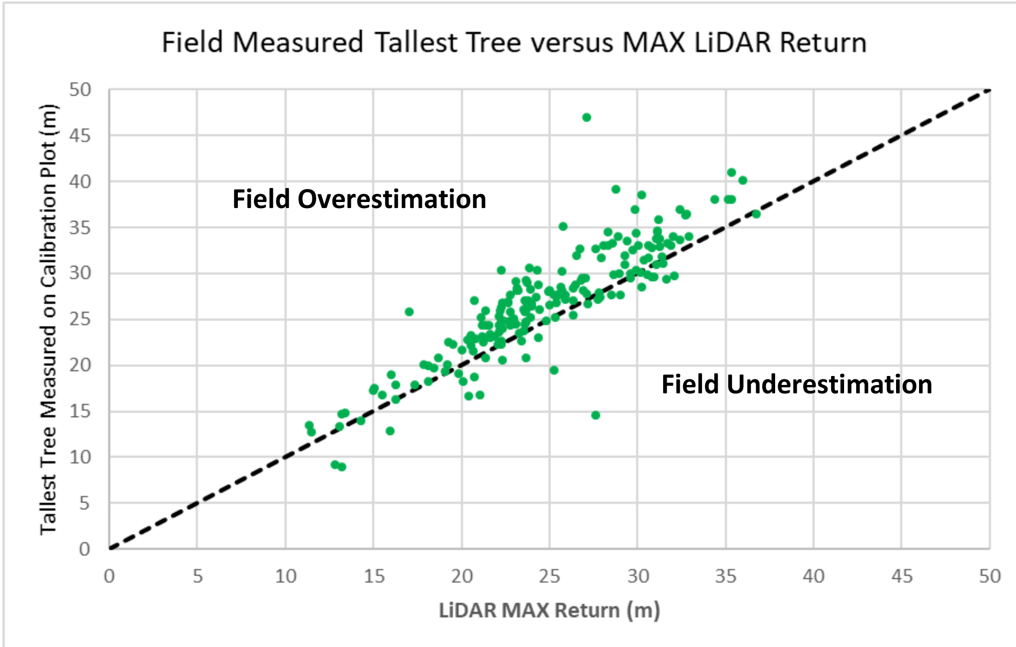


Figure 6 - The height of the tallest live tree on the plot is plotted against the maximum LiDAR return. The 1:1 line is given. Plots well below the 1:1 line (higher LiDAR MAX) are ones with tall dead trees (no field height) or overhanging trees outside the plot and not measured. There were a high number of plots where the tallest tree measured was quite a bit taller than the highest LiDAR return (above the 1:1 line).

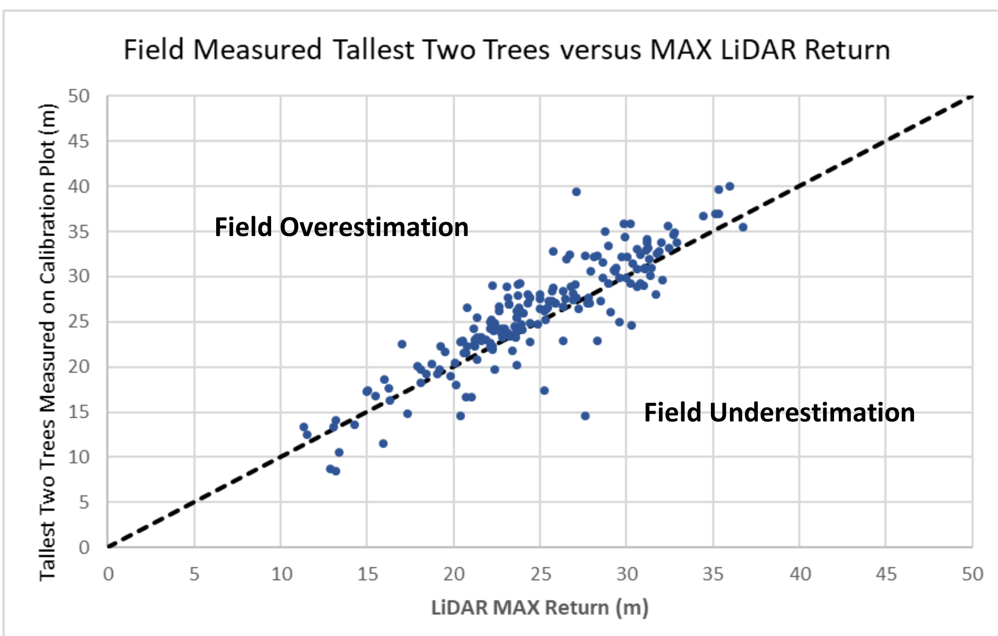


Figure 7 - The same as Figure 6 except the average of the two tallest trees is plotted on the y-axis

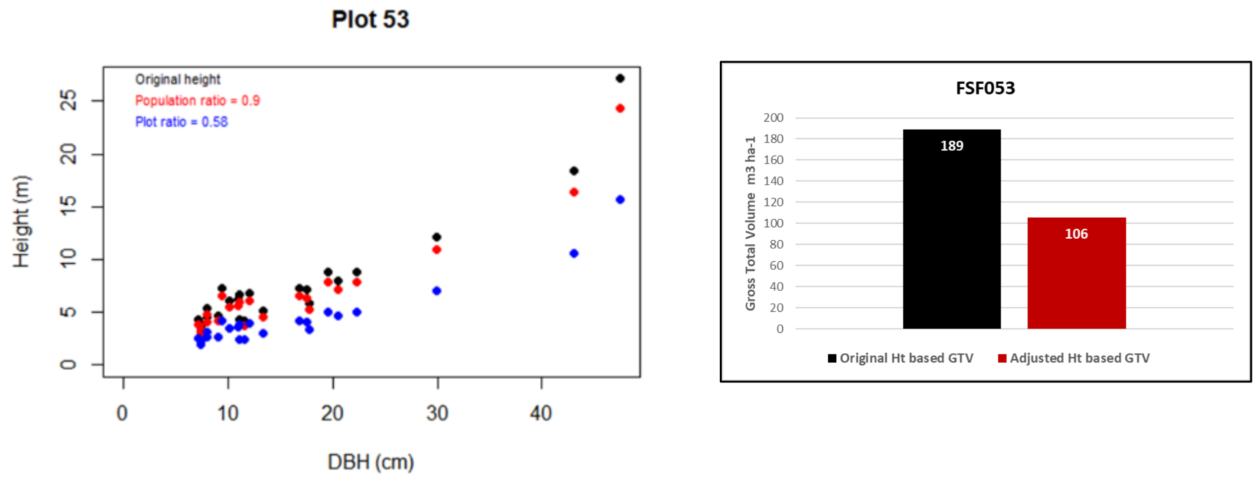


Figure 8 - For this plot with a too high field height, both the population and plot adjustments are downward. The impact to GTV is Unadjusted GTV 189 m3/ha, adjusted GTV = 106 m3/ha.

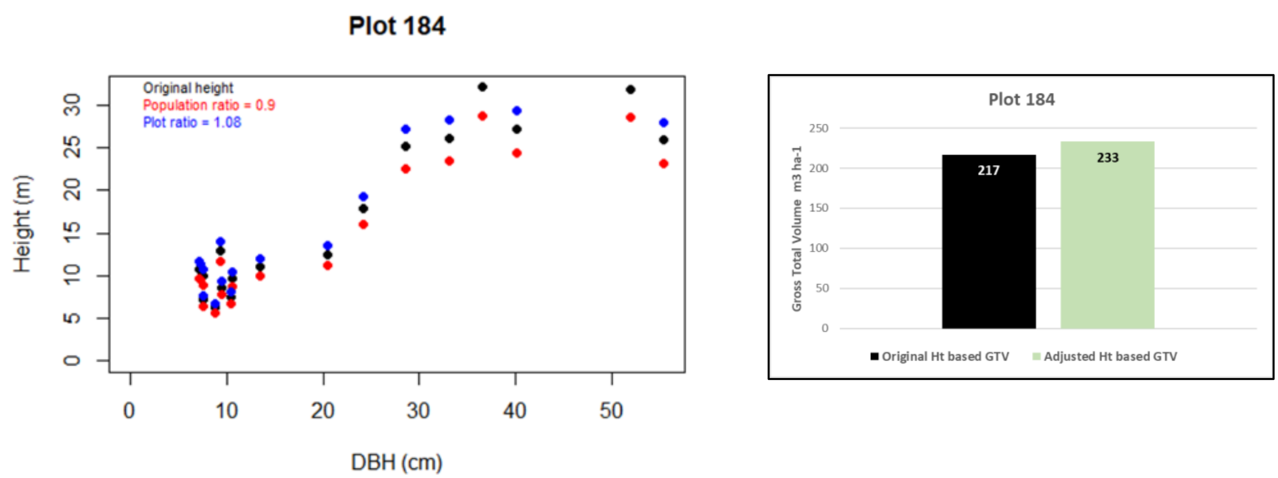


Figure 9 - Here is an example where the field crew underestimated the heights. The population ratio adjusts height down while the plot ratio adjusts height higher. The impact to GTV is Unadjusted GTV = 217 increased to GTV = 233 m3/ha for the adjusted heights.

Plot Compilation

For all live trees with DBH ≥ 7.1cm (common minimum DBH threshold for all VSN plot types) species, origin, Dbh, height, vigour and crown class were recorded. On some plots ages were recorded for a sample of trees. For dead trees ≥ 10cm (and > 2m), species, Dbh, height, vigour and decay class were recorded. Trees that had crowns leaning in or out of the plot were noted as were broken top trees.

Plots were summarized to per hectare values for all live trees ≥ 7.1cm. Dead trees were also summarized for their informational value in explaining potential differences noted between modeling results and plot summaries. However, dead trees were not used to calibrate the LiDAR models.

Table 2 - Inventory attributes summarized from calibration plots and predicted from LiDAR. Volume estimates came from Zakrzewski and Penner 1983. Biomass estimates came from Lambert et al. 2005.

Inventory Attribute	Units	Description
Stems	Stems ha^{-1}	Number of live trees
BA	m^2 ha^{-1}	Basal Area (Dbh $\geq$ 7.1cm)
BAmerch	m^2 ha^{-1}	Basal Area Merchantable (Dbh $\geq$ 9.1cm)
CDht	m	Average CoDominant-Dominant height
LoreyHeight	m	Lorey Height. Mean height weighted by basal area
TopHt	m	Top Height defined as height of the 100 largest DBH trees per hectare (irrespective of species)
QMD	cm	Quadratic mean diameter
GTV	m^3 ha^{-1}	Gross Total Volume (includes stump and top)
GMV_NL	m^3 ha^{-1}	Gross Merchantable Volume with no minimum piece length requirement. Stump height 30cm and upper diameter as per Ontario Scaling Manual (Table 3)
GMV_WL	m^3 ha^{-1}	Gross Merchantable Volume in 2.54 m log lengths • Stump height 30cm and upper diameter as per Ontario Scaling Manual (Table 3)
BA_Pole	m^2 ha^{-1}	Basal Area for the Pole size class. [9 < Dbh $\leq$ 25 cm]
BA_Sawlog	m^2 ha^{-1}	Basal Area for all Sawlog size classes. [Dbh $\geq$ 25 cm]
BA_SmSaw	m^2 ha^{-1}	Basal Area for the Small Sawlog size class [25 < Dbh $\leq$ 37 cm]
BA_MedSaw	m^2 ha^{-1}	Basal Area for the Medium Sawlog size class. [37 < Dbh $\leq$ 49 cm]
BA_LgSaw	m^2 ha^{-1}	Basal Area for the Large Sawlog size class. [Dbh > 49 cm]
GMV_Pole	m^3 ha^{-1}	Gross Merchantable Volume (_NL) with no minimum piece length requirement for the Pole size class. [9 < Dbh $\leq$ 25 cm] • Stump height 30cm and upper diameter as per Ontario Scaling Manual (Table 3)
GMV_Sawlog	m^3 ha^{-1}	Gross Merchantable Volume for all Sawlog size classes. [Dbh $\geq$ 25 cm]
GMV_SmSaw	m^3 ha^{-1}	Gross Merchantable Volume ((_NL)) with no minimum piece length requirement for the Small Sawlog size class. [25 < Dbh $\leq$ 37 cm] • Stump height 30cm and upper diameter as per Ontario Scaling Manual (Table 3)
GMV_MedSaw	m^3 ha^{-1}	Gross Merchantable Volume ((_NL)) with no minimum piece length requirement for the Medium Sawlog size class. [37 < Dbh $\leq$ 49 cm • Stump height 30cm and upper diameter as per Ontario Scaling Manual (Table 3)
GMV_LgSaw	m^3 ha^{-1}	Gross Merchantable Volume ((_NL)) with no minimum piece length requirement for the Large Sawlog size class. [Dbh > 49 cm] • Stump height 30cm and upper diameter as per Ontario Scaling Manual (Table 3)
Biomass	Tonnes ha^{-1}	Total above ground biomass (wood + bark + branches + foliage)
FSF_Smlog	m^3 ha^{-1}	**Must be modified by Species composition (hardwood species) proportions** Gross merchantable volume to Huntsville Forest Products upper diameter specifications for hardwoods

An approved provincial standard set of inventory attributes were summarized for model prediction. Table 2 lists the inventory attributes that were summarized for modeling (live trees with DBH $\geq$ 7.1cm unless noted) on the FSF. Individual tree volumes were calculated using Zakrzewski and Penner (2014) taper models developed for Ontario. No height estimation was required for the FSF dataset as each tree had a measured height. In the case of the FSF dataset, the "adjusted" height was used.

Table 3 - Minimum upper diameter limits for merchantable volume calculation by species group

Species	Minimum Diameter Outside Bark (DOB)
Hardwoods (except poplar/white birch)	18cm class, 17.1 cm
Conifers (except White and Red Pine, Hemlock	10cm class, 9.1 cm
White & Red Pine Hemlock	14cm class, 13.1 cm
Poplar, White Birch	14cm class, 13.1 cm
Source: OMNRF. 2020. Scaling Manual, Toronto. Queen's Printer for Ontario. 169 pp ISBN:978-1-4868-4495-1	

Individual tree total above ground biomass was calculated by species using the equations published in Lambert et al. (2005). Individual species equations were used when available. When no species coefficients existed, broader "hardwood" or "softwood" model coefficients were used.

Calibration Plot Spatial Positioning

Once target plot locations were identified, all established plots were spatially located with a survey grade GNSS system. Data was post–processed to meet required sub–metre positional requirements.

Exclusion of Calibration Plots

As noted earlier, LiDAR was acquired for the bulk of the FSF forest during the summer of 2019 and the majority of plot measurements were occurred between June 25, 2020, till September 19, 2020. Eight provincial Growth and Yield program plots were remeasured in September 2021 and included. The intent of the calibration plots is to capture vegetation conditions that match the LiDAR measurements. However, some calibration plots sampled structural conditions made up of trees too small (minimum Dbh threshold of 7.1cm or < 5m in height) to provide opportunity for summarization and inclusion in the modeling. Table 4 identifies the 22 plots excluded from the calibration of the LiDAR and their reason for removal. A total of 190 calibration plots remained available to produce the LiDAR inventory. Further filtering of calibration plots for model construction is discussed later.

The FSF calibration plots were assigned a FSF Forest Unit (FSF FU) based on the SQL presented in Appendix E. Because not all attributes required (Site Class, Stocking) to implement the FSF FU SQL were available for each calibration plot and/or the number of observations by FU were too small to report statistics on, a broader aggregation of calibration plots to a forest type was carried out. Table 5 identifies the FSF FU assignment to FSF Forest Type (FT). A summary of the calibration plots by FT is provided in Table 6. Of note is the number of calibration plots per FT. Some conditions seem under sampled while others appear oversampled. This disparity in sample size by FT is a function of the structural sampling approach adopted by the province of Ontario. Forest conditions with a wide range of vertical structures (i.e., pine shelterwoods) were sampled more than more "simple" structures often found in conditions like pure red pine plantations.

LiDAR Data Processing

Raw classified LiDAR LAS datasets were provided to the province by the vendor. Standard American Society for Photogrammetry and Remote Sensing (ASPRS) classification coding standards were used by

Table 4 - FSF calibration plots excluded from analysis

Plot Number	Reason for Exclusion
VSN360004	No live trees
VSN360005	No live trees
VSN360016	Clearcut after LiDAR acquired
VSN360017	No live trees
VSN360018	Clearcut
VSN360040	Large field measured 49m tall not found on or near plot – GPS Error?
VSN360049	Managed Layer <20 years old
VSN360083	No tree data collected
VSN360087	LiDAR returns are from hydro wires with no trees tallied
VSN360123	Microburst after Lidar and before plot established
VSN360143	No live trees
VSN360157	LiDAR returns are from hydro wires with no trees tallied
VSN360160	Burial Site noted – Incomplete plot measurement
VSN360188	Plot tally and point cloud mismatch – GPS error??
VSN360209	Managed layer <20 years old
VSN360213	No Live Trees
VSN360224	<20 years old
VSN360226	Microburst after Lidar and before plot established
VSN360*132*	Plots excluded as Zq99 <5m
VSN360*165*	Plots excluded as Zq99 <5m
VSN360*201*	Plots excluded as Zq99 <5m
VSN360*219*	Plots excluded as Zq99 <5m

Table 5 - FSF Forest Type aggregation of FSF Forest Units used for calibration plot summaries.

Reporting Forest Type (FT)	**FSF SC FU**
BY – Yellow Birch	BY
He - Hemlock	He
Intol – Intolerant Hardwoods	Bw , Po
Low – Lowland	Sb, LC, Ce, LWMW
MW - Mixedwoods	MWR, MUS
OAK - Oak	OAK
Pine – White/Red Pine	PWUS4, PWUSC, PWOR, PWST
PJ – Jack Pine	PJ1
PR – Red Pine	PR
SF – Spruce Fir	SF
TolHwd – Tolerant Hardwoods	HDSL1, HDSL2, HDUS

the vendor. Classification codes (2) ground , (3) low vegetation , (4) medium vegetation and (5) high vegetation return data only were processed. LAStools (LAStools, 2021) was used to “normalize” the LiDAR returns to the terrain (converting “z” height from elevation to height above ground). An additional script was implemented to compress the LAS formatted files to a space efficient LAZ format.

A modeling predictor set on a 20m x 20m grid was created for the 2018 LiDAR data set using the lidR (Roussel and Auty 2020, Roussel et al. 2020) software package in R (R development Core Team 2020). A total of 112 potential LiDAR predictors were derived from structural statistical queries of all-return, normalized point cloud data. Following testing of predictive model performance from thresholding the returns at 0 m and 2.0 m, a decision was made to use all returns greater than 0 m for modeling inventory attributes on the FSF. This choice of threshold was also documented in other studies in Ontario (White *et al.* 2021, Woods *et al.* 2011). Data "z" spikes were removed by dropping any returns > 48m. A complete list and description of the LiDAR predictors created is provided in Appendix A. Predictors that were selected for use in the predictive models are indicated. LiDAR predictors that exhibiting artifacts of banding were not used in model development (i.e. counts of points).

LiDAR Model Development

A non-parametric Random Forest (RF) model (Liaw and Wiener 2002) solution via the statistical package R (R development Core Team 2020) was used for the prediction of inventory attributes. All model predictions were made at the plot scale and at a 20 m raster cell (matching the 400 m^2 plot size) with the model mtry parameter set to the default (number of predictors/3) and the parameter ntree (number of trees to construct) set to 1000. Only calibration plots with zq99 > 5m were used in the prediction of stand level metrics to better align with the calibration plot minimum DBH of 7.1 cm. This filter resulted in the dropping of an additional calibration plot from the modeling but ensured that only plots with at least some merchantable sized trees were utilized in the models and the predictions made at the landscape level. In the prediction of size class attributes and merchantable volume attributes, calibration plots with Zq99 > 9m were used as plots with Zq99 ≤ 9m had little or no merchantable volume.

Investigation of the initial modeling of specific inventory attributes of (BA, BA_merch, and QMD), identified that calibration plots consisting of tolerant and mid-tolerant hardwoods (> 50% hardwoods) were being generally overpredicted by a single un-stratified RF model intended to model All-Forest species conditions. The desire to utilize a nonparametric modeling approach like RF for the derivation of a LiDAR inventory is to eliminate the requirement for species information, usually only interpreted and provided at the polygon scale. In most situations, a dynamic RF modeling solution of matching point-cloud distribution statistical measurements at a grid cell level (20m x 20m) and a desired inventory attribute summaries, without any a priori knowledge of species, has resulted in flexible models (i.e., White et al. 2021) capable of predicting attributes a range of species conditions. However, it became clear for the FSF forest and this SPL dataset, that creating a stratified, 2 RF model solution resulted in better predictions for some of the inventory attributes (a basal area comparison of a single-strata vs 2-strata is presented in Figure 10). The list of inventory attributes predicted by a single or stratified RF model approach and modeling strata description is presented in Table 7.

LiDAR predictions for each attribute were made independently. In most cases (e.g., DomCodom height, Top Height, Lorey Height) this works well. However, to ensure some logic and biological consistency in predictions, some attributes were predicted as a fraction of other attributes. An example of such an

Table 6 – Statistics – Mean (range) of calibration plots by FSF Forest Type[1]

Forest Type	No Plots	Breast Height Age (yrs)[2]	TopHt (m)	CDHT (m)	Lorey Ht (m)	Stems (ha)	Basal Area (m^2 ha^{-1})	QMD (cm)	GTV (m^3 ha^{-1})	GMV_NL (m^3 ha^{-1})	GMV_WL (m^3 ha^{-1})	Biomass (Tonnes ha^{-1})
BY	8	72 (42 - 155)	21.0 (17.3 – 24.4)	18.7 (15.8 - 22.7)	19.3 (16.6 - 21.8)	641 (350 - 975)	26.1 (16.3 - 29.4)	23.5 (18.7 - 30.6)	198 (120 - 226)	138 (97 - 192)	126 (87 - 186)	172 (105 - 195)
He	10	105 (N=8) (58 - 200)	22.6 (15.3 - 28.8)	20.5 (13.9 - 24.1)	20.5 (13.3 - 25.4)	618 (300 - 1200)	41.2 (10.3 - 52.7)	30.3 (16.6 - 39.2)	307 (53 - 436)	263 (26 - 393)	253 (21 - 383)	230 (49 - 294)
Intol	2	57 (N=2) (39 - 75)	20.2 (19.9 – 20.5)	17.2 (15.2 - 19.2)	17.5 (15.7 - 19.3)	1263 (550 - 1975)	29.0 (27.8 - 30.2)	19.9 (13.4 - 26.4)	214 (189 - 239)	144 (97 - 192)	134 (86 - 182)	160 (113 - 207)
Low	8	70 (N=8) (28 - 110)	15.6 (N=8) (10.8 - 26.3)	14.0 (9.1 - 21.4)	14.4 (9.9 - 22.7)	694 (125 - 2100)	16.2 (1.2 - 39.8)	16.7 (9.3 - 25.1)	100 (6 - 267)	78 (1 - 210)	73 (1 - 200)	59 (4 - 173)
MW	8	60 (N=7) (23 - 136)	19.7 (12.3 - 22.9)	17.4 (9.5 - 20.8)	16.2 (10.6 - 19.7)	1016 (650 - 1650)	28.2 (10.2 - 51.8)	18.9 (12.5 - 27.2)	201 (46 - 398)	158 (23 - 337)	148 (19 - 320)	139 (35 - 312)
Oak	2	76 (54 - 98)	22.6 (21.5 - 23.8)	19.2 (18.4 – 20.0)	19.8 (17.5 - 22.1)	688 (575 - 800)	32.0 (24.4 - 39.6)	24.7 (19.7 - 29.6)	277 (185 - 368)	222 (138 - 307)	210 (123 - 297)	242 (148 - 336)
Pine	46	93 (N=44) (26 - 135)	26.2 (13.4 - 34.4)	24.2 (10.4 - 31.6)	23.3 (12.2 - 30.8)	566 (25 - 1475)	27.5 (2.2 - 96.4)	27.7 (14.2 - 69.3)	276 (16 - 1055)	247 (14 - 994)	242 (13 - 987)	145 (8 - 552)
Pj	2	54 (53 - 54)	11.8 (10.3 - 13.2)	10.8 (9.6 - 12)	10.7 (9.5 - 11.8)	775 (725 - 825)	12.9 (11.7 - 14.2)	14.6 (14.3 - 14.8)	61 (48 - 75)	45 (33 - 57)	40 (29 - 51)	39 (32 - 46)
Pr	15	72 (N=14) (24 - 126)	26.2 (17.3 - 33.5)	25.3 (17 - 32.9)	24.9 (17 - 31.5)	640 (25 - 1275)	33.7 (9.3 - 68.9)	30.0 (19.2 - 68.7)	377 (109 - 856)	349 (106 - 812)	339 (105 - 799)	181 (58 - 410)
SF	14	59 (N=13) (22 - 93)	18.9 (9.5 - 27.6)	15.5 (N=13) (8.4 - 24.1)	15.7 (8.6 - 27.6)	1077 (25 - 2050)	19.2 (0.5 - 53.5)	16.4 (10.5 - 30.5)	127 (6 - 487)	102 (5 - 459)	96 (5 - 451)	75 (3 - 255)
TolHwd	75	80 (N=68) (28 - 129)	21.9 (13.2 - 30.7)	19.7 (10.7 - 28.3)	19.8 (10.8 - 27.9)	636 (150 - 1700)	23.9 (9.5 - 45.6)	23.1 (12.6 - 37.9)	189 (50 - 444)	139 (14 - 395)	130 (8 - 387)	162 (47 - 385)
All	**190**	**80 (N=176) (22 - 200)**	**22.6 (9.5 – 34.4)**	**20.5 (N=189) (8.4 - 32.9)**	**20.3 (8.6 - 31.5)**	**675 (25 - 2100)**	**26.1 (0.5 - 96.4)**	**24.1 (9.3 - 69.3)**	**222 (6 - 1055)**	**184 (1 - 994)**	**176 (1 - 987)**	**151 (3 - 552)**

[1] FSF Forest Unit syntax was used to assign FU. However, some information like Site Class (used in some FU assignment) was not available at the plot level so was not used. As a result, broader Forest Types were assigned.

[2] Breast height age is the average breast height age of dominant/codominant trees with measured ages. Trees were not measured for age on all plots and the sample sizes for age are less than the number of plots.

attribute is gross merchantable volume (GMV). Actual GMV is never larger than gross total volume (GTV). To constrain the prediction of GMV, the fraction of GMV/GTV was predicted. Different constraining approaches were tested and the rationale for the method chosen for the various volume predictions is described below.

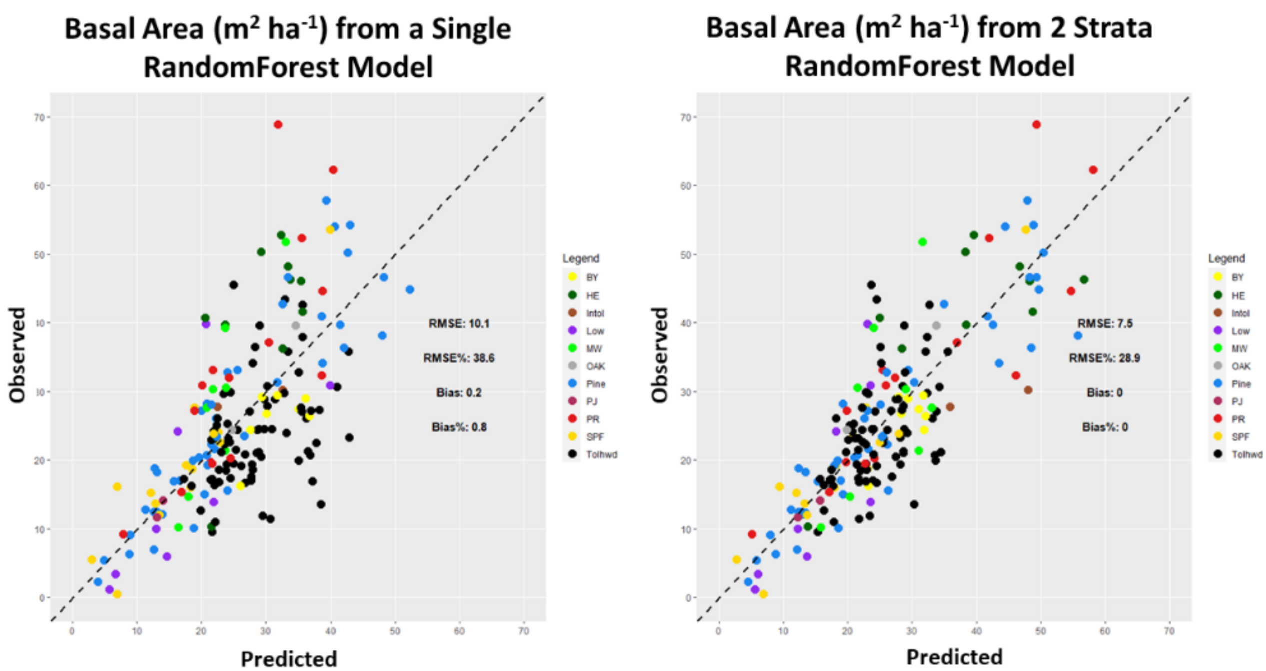


Figure 10 - Comparison of a single RF model solution versus a stratified RF model solution for basal area on the FSF (units are m2 ha-1)

Table 7 - Modeling method adopted for the FSF.

Inventory Attribute	Modeling Approach
Topht	Single Strata Model
CDht	Single Strata Model
LoreyHt	Single Strata Model
Vbar_gtv	Single Strata Model
Biomass	Single Strata Model
gmvnl_ratio	Single Strata Model
gmvwl_ratio	Single Strata Model
FSF_Smlog_ratio	Single Strata Model
Ba by Size Class	Single Strata Model
GMV by Size Class	Single Strata Model
Basal Area	Two Strata Model -Tolerant Hardwood >50% , Conifer + Intolerant Hardwoods
Basal Area Merch	Two Strata Model -Tolerant Hardwood >50% , Conifer + Intolerant Hardwoods
QMD	Two Strata Model -Tolerant Hardwood >50% , Conifer + Intolerant Hardwoods

Gross Total Volume (GTV)

Rather than predicting GTV directly, it was predicted as a function of basal area (BA) and the volume to basal area ratio (vbar). Both options were tested and resulted in similar RMSEs and biases. The vbar option to estimate GTV was chosen as it may help preserve a bit of the relationship between BA and GTV by ensuring the predicted vbar is always within the range observed in the calibration data.

1. BA is predicted directly.
2. vbar_GTV = GTV/BA is predicted directly.
3. GTV is calculated as predicted BA x predicted vbar_GTV

Gross Merchantable Volume (GMV)

All merchantable volumes are constrained to be less than or equation to the predicted GTV. This is accomplished through predicting the ratio GMV/GTV.

1. Predict GTV using the method described above
2. Predict ratio GMV = GMV/GTV directly
3. Calculate GMV as GTV x ratio GMV

This is mathematically equivalent to constraining the vbar_GMV to be less than or equal to vbar_GTV.

$$ratio_{GMV} = \frac{GMV}{GTV} = \frac{vbar\_GMV}{vbar\_GTV} = \frac{GMV/_{BA}}{GTV/_{BA}}$$

All merchantable volumes (GMV_NL, GMV_WL and FSF_Smlog) were constrained against GTV. Merchantable volumes (i.e., GMV_NL and GMV_WL) were not constrained to be greater or equal to each other.

Size Class estimates of Merchantable Basal Area and GMV_NL

Size class estimates of merchantable volume and basal area were constrained to always sum to either predicted GMV_NL or Basal Area_merch (BAmerch). An example of the method for basal area by size class is described below. First, the merchantable BA was split into BAMedLg and BASmPole. Then BAMedLg was split into BAmedium and BAlarge and BASmPole was split into BAsmall and BApole. Similar splits were made for GMV_NL

1. Calculate BAmerch = BaPoles + BAsmall + BAmedium + BAlarge from calibration plot data
2. Calculate a BAmedium + BAlarge fraction of plot BAmerch from calibration plot data
    i. BAMedLg_frac <- (BAlarge + BAmedium)/BAmerch
3. Calculate fraction of Large BA in Medium and Large Sawlogs from calibration plot data
    i. BALg_ratio <- BAlarge/(BAlarge + BAmedium)
4. Calculate fraction of Small BA in Small sawlogs and Poles from calibration plot data
    i. BASm_ratio <- BAsmall/(BAsmall + BApoles)

5. Develop RF models for: BAmerch, BALg_ratio, BASm_ratio

6. Calculate basal area in medium and large sawlogs (BAMedLg)

```
BA_MedLg <- (BA_MedLgSawFrac * BAmerch)
```

7. Calculate the proportion of the predicted BA_MedLg is Large sawlog where P99 $\geq$ 20 else be set to 0 & resulting in value moves to the Medium sawlog

```
BA_LgS <-  ifel(zq99 >= 20, (BA_MedLg * BA_LgRatio), 0)
```

8. Calculate the BA_MedLg sawlog where P99 $\geq$ 15 else be set to 0 & resulting in value moves to the small sawlog and pole basal area

```
BA_MS <- ifel(zq99 > 15, (BA_MedLg - BA_LgS),0)
```

9. Calculate the Basal area for SmallSawlog & Poles

```
BA_SmPl <- (BAmerch - BA_LgS - BA_MS)
```

10. Calculate the BA for Small Sawlogs

```
BA_SmS <- (BA_SmPl * BA_SmRatio)
```

11. Calculate Pole BA as the difference between predicted BAmerch and predicted Large, Medium and Small sawlog basal areas

```
BA_Pole <- (BAmerch - BA_LgS - BA_MS - BA_SmS)
```

Table 8 indicates which attributes were predicted directly from the statistical predictor summaries of the raw LiDAR point cloud. Table 8 indicates which inventory attributes are calculated as a fraction of another one to help ensure logical predictions.

Table 8- Inventory attributes predicted directly from the point cloud predictors.

Inventory Attribute
TopHt
CDht
LoreyHeight
BasalArea
QMD
Biomass

Table 9 - Description of attributes and their calculations predicted indirectly. All attributes are summarized from > 7cm unless noted (P_ = Predicted)

Inventory Attribute	Calculation
Stems	Stems = (P_BasalArea / P_QMD^2) / 0.00007854
GTV	GTV = P_BasalArea * P_VBAR_GTV
GMV_NL	GMV_NL = P_GTV * P_GMV_NL_ratio
GMV_WL	GMV_WL = P_GTV * P_GMV_WL_ratio
BA_Poles	As described above [9 < Dbh ≤ 25 cm]
BA_SmS	As described above [25 < Dbh ≤ 37 cm]
BA_MedS	As described above [37 < Dbh ≤ 49 cm]
BA_LgS	As described above [Dbh > 49 cm]
GMV_Poles	As described above [9 < Dbh ≤ 25 cm]
GMV_SmS	As described above [25 < Dbh ≤ 37 cm]
GMV_MedS	As described above [37 < Dbh ≤ 49 cm]
GMV_LgS	As described above [Dbh > 49 cm]
FSF_Smlog	FSF_Smlog = P_GMV_NL * P_FSF_Smlog_ratio * hardwoods percent (not including Ironwood)

LiDAR Model Results

All LiDAR predictions are based on the LiDAR structure statistics and the field plot measurement summaries only[3]. Figure 11 illustrates the observed versus the predicted estimate for each LiDAR model. The diagonal dashed line indicates a perfect match between the measured plot summary and the prediction.

Plot level Validation

All calibration plots were used in model training and prediction. As a result, no independent plots were available to test model prediction error with. A “Cross Validation” (CV) can be used to estimate prediction error at the plot scale (20m x 20m) in the absence of an independent validation data set. V-fold CV error is generated by dividing the data set randomly into *V* equal parts. Training for the model is done on *V-1* parts and testing is done on the remaining part. This is repeated many times (10 times in this study) and the error rate estimate is an average of the results.

RMSE and Bias were calculated using the following equations:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)^2}{n}},$$

$$\text{RELATIVE RMSE} = \frac{\text{RMSE}}{\bar{Y}},$$

$$\text{BIAS} = \frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)}{n},$$

$$\text{RELATIVE BIAS} = \frac{\text{BIAS}}{\bar{Y}}.$$

[3] The field measurement summaries include species composition and age. However, they were not used in modeling except to use a tolerant hardwood model vs. other as noted in Table 6.

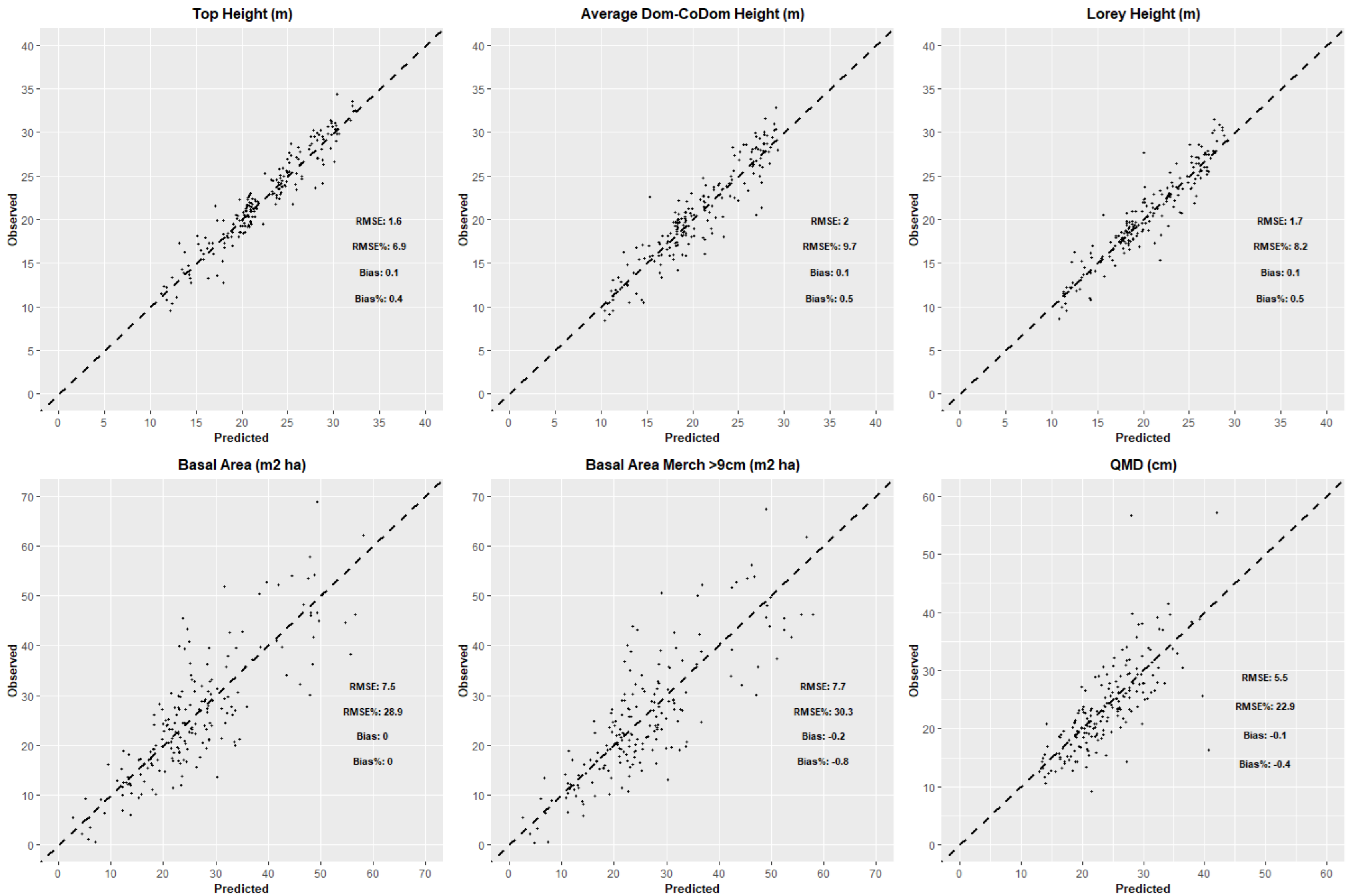


Figure 11 - Modeling results of Observed versus Predicted for selected inventory attributes on the FSF. Error statistics are based on a 10-fold Cross Validation sample.

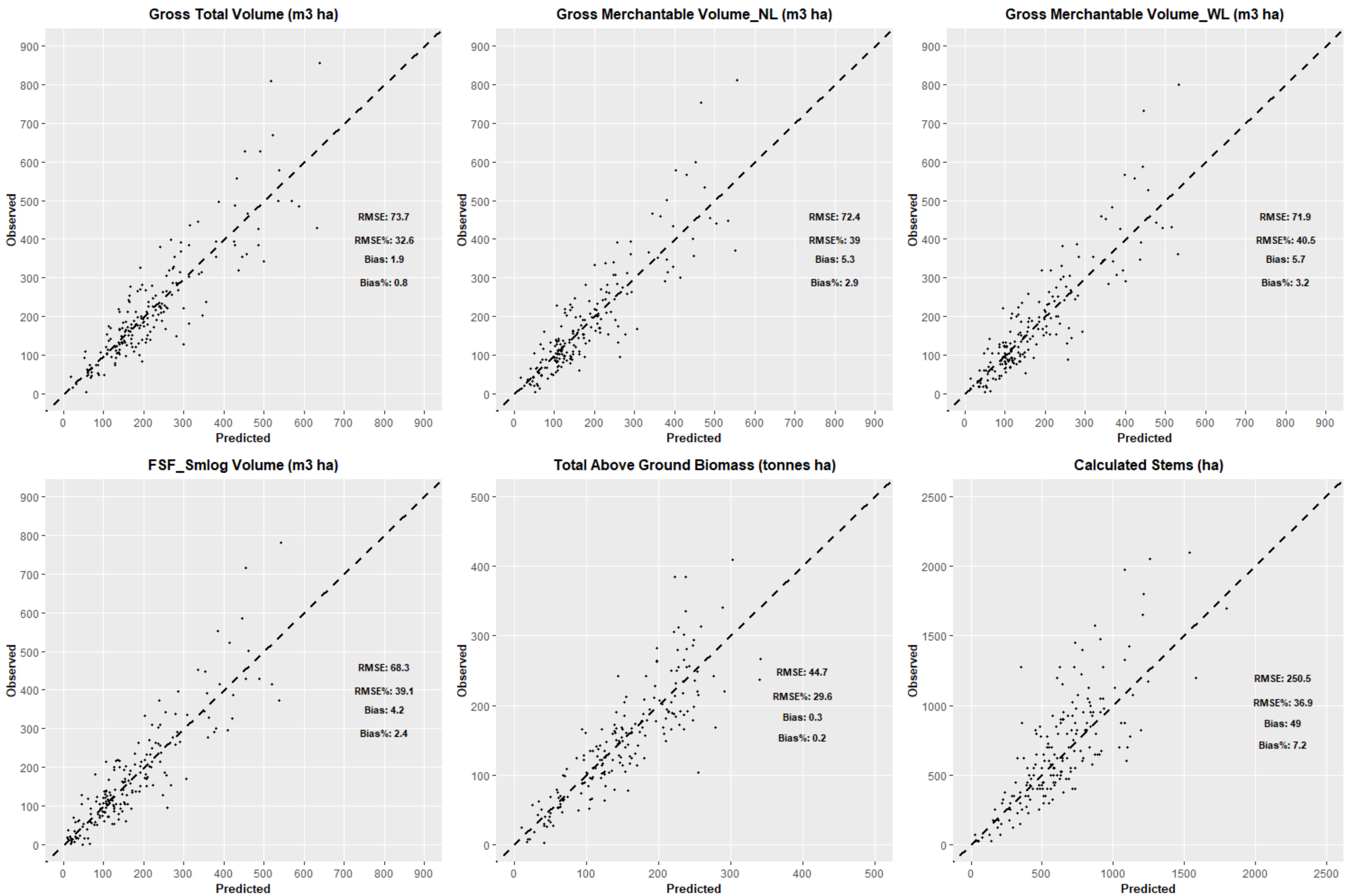


Figure 11 continued - Modeling results of Observed versus Predicted for selected inventory attributes on the FSF. Error statistics are based on a 10-fold Cross Validation sample.

Table 10 - Plot level validation statistics using a 10-fold Cross Validation methods for the FSF

	Observed				10-Fold Cross Validation (CV)					
Inventory Metric	N	Mean	Min	Max	P_Mean	P_SE	RMSE	% RMSE	BIAS	% BIAS
CDHT m	189	20.5	8.4	32.9	20.4	0.4	2.0	9.7	0.09	0.44
TOPHT m	190	22.6	9.5	34.4	22.5	0.4	1.6	6.9	0.06	0.27
LoreyHt m	190	20.3	8.6	31.5	20.2	0.4	1.7	8.2	0.1	0.1
BA m^2 ha^{-1}	190	26.1	0.5	96.4	26.1	0.8	7.5	28.9	0.0	0.0
BA merch m^2 ha^{-1}	190	25.4	0.4	95.0	25.6	0.8	7.7	30.3	-0.2	-0.8
QMD cm	190	24.1	9.3	69.3	24.2	0.5	5.5	22.9	-0.1	-0.4
GTV m^3 ha^{-1}	188	226	6.0	1055	224	9.3	73.7	32.6	1.9	0.8
GMV_NL m^3 ha^{-1}	188	186	5.0	994	180	8.6	72.4	39	5.3	2.9
GMV_WL m^3 ha^{-1}	188	178	4.6	988	172	8.5	71.9	40.5	5.7	3.2
Biomass T ha^{-1}	190	151.1	3.0	552.4	150.8	5.3	44.7	29.6	0.3	0.2
Stems ha^{-1}	190	678	25	2100	629.0	21.0	251	36.9	49	7.2

Plot level 10-fold CV comparisons of root mean square error (RMSE) and bias are presented by inventory attribute in Table 10. CV RMSE (%) AND bias (%) are graphically presented in Figure 12. These results reflect modeling of all species/silviculture/origin based solely on LiDAR point cloud structure and at the plot or 20 x 20m grid scale. The RMSE is a measure of how well the model performed. It is the square root of the average squared distance between the predicted values and the observed values in the dataset. The lower the RMSE, the better the modeling results. Bias is the difference between the average prediction and the correct value. Similarly, a lower bias is always preferred.

Although the LiDAR models were not fit by forest type, the results can be presented in that manner to get a sense at the 20m x20m grid scale how a model is performing overall. Figure 13 provides an example of 4 predicted inventory attributes by comparing the observed calibration plot mean and the CV mean prediction (along with standard error). **Note, the number of plots by forest type varies and the results should be viewed in that light. The percent of the managed forest land base that each forest type represents is also presented.**

Appendix B provides a tabular and graphical summary of CV plot level predictions by forest types on the FSF forest.

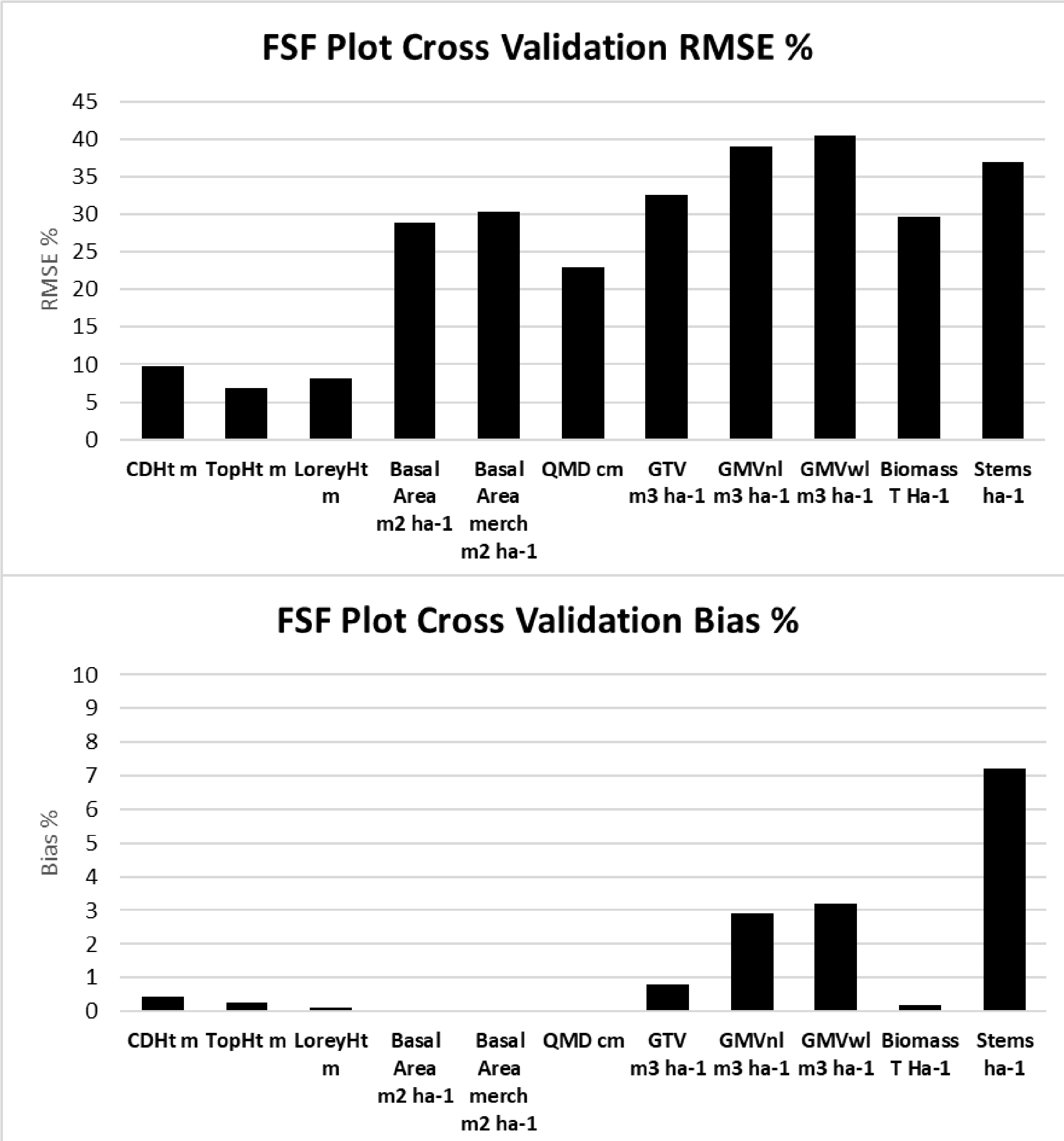


Figure 12 - RMSE (%) and Bias (%) for inventory attribute validation using a 10-fold Cross Validation.

Figure 13 - Comparison of CV observed and predicted means of four selected inventory attributes. Standard Error is presented for the predictions.

LiDAR Prediction Raster Surface Adjustments

Predicted raster products were modified to align pixel predictions with the limitations of the calibration plot network (DBH > 7.1 cm). Table 11 identifies the 99th percentile LiDAR height that was used as a threshold. Pixels with a Zq99 < 5m were not expected to have trees with DBH ≥ 7.1 cm. Pixels with a Zq99 < 9m were not expected to have merchantable sized trees.

Table 11 - Adjustments to LiDAR raster predictions based on zq99 thresholds.

Raster Surface	Zq99 Threshold	Adjustment of Raster Predictions
CDHT	5 m	CDHT predictions replaced with zq99 value where zq99 < 5 m
TOPHT	5 m	TopHt predictions set to **NULL** where zq99 < 5 m
LoreyHt	5 m	LoreyHt predictions set to **NULL** where zq99 < 5 m
Basal Area	5 m	Basal Area predictions set to 0 where zq99 < 5 m
QMD	5 m	QMD predictions set to **NULL** where zq99 < 5 m
Biomass	5 m	Biomass predictions set to 0 where zq99 < 5 m
Stems	5 m	Stems calculation set to 0 where zq99 < 5 m
Basal Area merch	9 m	BA_merch predictions set to 0 where zq99 < 9m
BA_SmPoles	9 m	BA_SmPoles predictions set to 0 where zq99 < 9m
BA_LgPoles	9 m	BA_LgPoles predictions set to 0 where zq99 < 9 m
BA_SmSaw	9 m	BA_SmSaw predictions set to 0 where zq99 < 9 m
BA_LgSaw	9 m	BA_LgSaw predictions set to 0 where zq99 < 9 m
GTV	9 m	GTV predictions set to 0 where zq99 < 9 m
GMV_NL	9 m	GMV_NL predictions set to 0 where zq99 < 9 m
GMV_WL	9 m	GMV_WL predictions set to 0 where zq99 < 9 m
GMV_Util	9 m	GMV_SFL predictions set to 0 where zq99 < 9 m
GMV_SmPoles	9 m	GMV_NL_SmPoles predictions set to 0 where zq99 < 9 m
GMV_LgPoles	9 m	GMV_NL_LgPoles predictions set to 0 where zq99 < 9 m
GMV_SmSaw	9 m	GMV_NL_SmSaw predictions set to 0 where zq99 < 9 m
GMV_LgSaw	9 m	GMV_NL_LgSaw predictions set to 0 where zq99 < 9 m

The LiDAR derived CDHT raster for the FSF is provided in (Figure 14). Additional examples of derived inventory raster outputs are provided in Appendix C.

Stand Level Validation

Most forest management decisions are not made at a raster grid cell (20 m x 20 m) resolution. Usually, decisions are made on an aggregation of grid cells within a forest stand or harvest block. Pre-harvest operational cruising (OPC) is conducted as part of planned forest management activities on the FSF. These OPC activities, although not intensive, provide a sample of planned harvest block conditions to support silvicultural prescription development. In these mixed species stand conditions, sometimes species, or areas, that are not going to be managed, are not sampled with cruising.

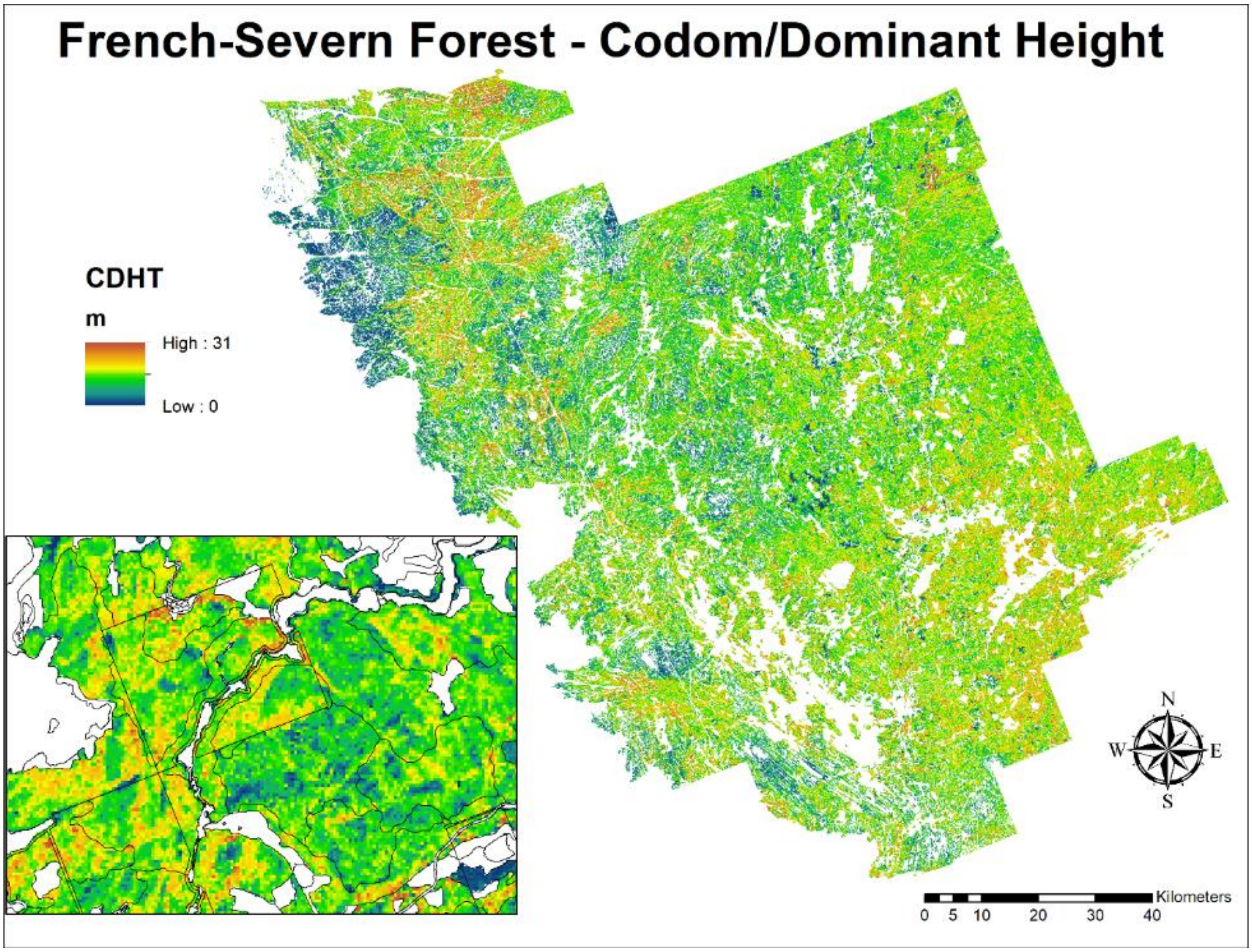


Figure 14 - LiDAR derived FSF Dominant/Codominant Height raster

OPC data for harvest blocks cruised in 2018 and 2019 and not harvested before the LiDAR was acquired were made graciously available by Westwind Forest Stewardship Inc. SFL. In many situations, harvest blocks were made up of multiple stands. To provide a validation dataset with enough cruising observations to be more confident in a comparison, the blocks were split back to the original stands and stands that had a minimum of 3 (only one stand had 3 with most having 4 or more) cruising stations were selected. The number of eligible validation stands was further refined for situations where portions of the stands containing pockets of species (i.e., hemlock) were not sampled at all by the OPC (as that species was not to be managed). Examples of cruised stands that were not included in the validation are presented in Appendix F.

A total of 29 stands were used for the validation exercise. These stands sampled a range of silvicultural conditions from hardwood selection, or uniform shelterwood first cut/seed cut scenarios to white/red pine uniform shelterwood seed cuts or last cuts. As is typical in the Great Lakes St. Lawrence Forest region, stand species and site conditions for most of these validation stands offer different levels of variable conditions (mixed-species, clumps of conifer in hardwood dominated stands, shallow sites over bedrock, exposed bedrock, linear features of trees due to site conditions, etc.). The required number of cruising observations to provide estimates to some level of stated statistical rigour is usually way beyond what is operationally feasible. As a result, some validation stands are sampled at a low sampling intensity

OPC is intended to support silvicultural prescriptions development. Data collected consists of basal area by species, management size class and quality. Additional notes on levels of existing regeneration and presence of tree disease (Beech Bark Disease) are also included. Only stand merchantable basal area, and merchantable basal area for the poles and sawlog size-class can be compared against the LiDAR predictions. Table 12 provides a list of the validation stand conditions. They are presented by Forest-type-Silvicultural system. A pseudo-sampling intensity has been calculated to provide a sense of the "confidence" of the population observations. Figure 15 provides some examples of cruising station spatial distribution of some of the stands used in validation.

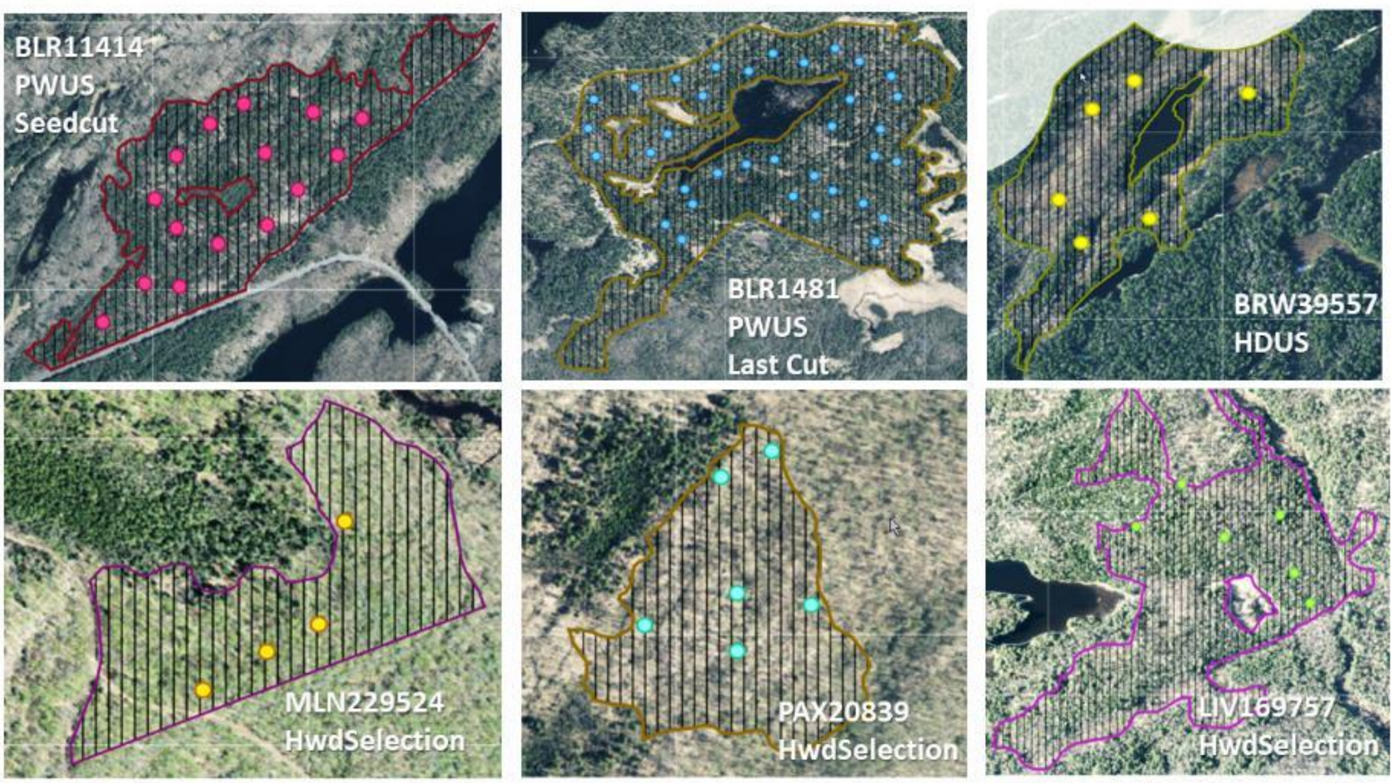


Figure 15 - Examples of sampling stations established in various OPC stand conditions (leaf-off imagery).

Table 12 - Description of FSF OPC validation stands. (Note – pseudo sampling intensity based on a station plot area = 0.04 ha).

Stand	Forest-Type-Silvicultural System	Cruising Stations	Stand Area (Ha)	Basal Area Merch (m^2 ha^1)	Pole Basal Area (m^2 ha^1)	Sawlog Basal Area (m^2 ha^1)	Pseudo Sampling Intensity (%)
BLR11414	Hwd_Sel	15	54.4	32.0	8.9	23.1	1%
BRW39557	Hwd_Sel	6	19.8	28.3	9.7	18.7	1%
LIV169757	Hwd_Sel	6	31.2	18.3	7.3	11.0	1%
MCR92293	Hwd_Sel	5	30.4	24.0	8.8	15.2	1%
MLN229254	Hwd_Sel	3	11.3	25.3	6.7	18.7	1%
MLN229898	Hwd_Sel	6	25.3	21.3	5.0	16.3	1%
MLN230330	Hwd_Sel	7	29.7	20.0	4.0	16.0	1%
MLN231616	Hwd_Sel	7	22.7	24.6	5.4	19.1	1%
PAX19118	Hwd_Sel	5	24.1	35.6	12.0	24.4	1%
PAX19343	Hwd_Sel	4	28.1	24.0	10.0	14.0	1%
PAX20065	Hwd_Sel	4	17.5	24.0	7.5	16.5	1%
PAX20433	Hwd_Sel	6	8.6	28.0	7.6	20.5	3%
PAX20637	Hwd_Sel	6	36.7	25.0	6.7	18.3	1%
PAX20674	Hwd_Sel	10	43.4	25.8	9.2	16.6	1%
PAX20839	Hwd_Sel	6	10.5	29.0	7.3	21.7	2%
PAX21206	Hwd_Sel	6	17.8	23.0	6.0	17.0	1%
PAX21439	Hwd_Sel	12	40.5	22.8	6.3	16.5	1%
PAX21683	Hwd_Sel	7	31.4	24.9	8.3	16.6	1%
BLR11543	Hwd_US	6	13.1	18.0	8.7	9.3	2%
MLN226330	Hwd_US_FirstCut	11	29.4	21.8	6.9	14.9	1%
MLN228322	Hwd_US_FirstCut	4	16.6	30.5	7.5	23.0	1%
MLN232398	Hwd_US_FirstCut	9	53.7	20.2	3.8	16.4	1%
MLN227754	Hwd_US_SeedCut	8	23.5	21.3	4.5	16.3	1%
PAX18213	Hwd_US_SeedCut	4	6.7	22.0	6.5	15.5	2%
BLR1481	Pine_US_LastCut	35	133	14.1	4.2	9.9	1%
BLR1890	Pine_US_LastCut	5	15.1	14.4	4.0	10.4	1%
BLR11714	Pine_US_SeedCut	12	14.2	33.2	8.0	25.3	3%
LAU12623	Pine_US_SeedCut	16	46.6	20.1	3.5	16.8	1%
MLN229812	Pine_US_SeedCut	5	15.4	30.8	10.4	20.4	1%
	Mean	**8**	**29.3**	**24.2**	**7.1**	**17.2**	**1%**

Validation Results

Figure 16 graphically displays the average validation stand prediction results (N=29) for All-Forest types for three attributes: BAmerch, Pole basal area, and Sawlog basal area. Figure 17 provides the same information but separated by FT and silvicultural system. Figure 18 displays a more detailed comparison of individual validation stands observations and predictions for selected inventory attribute using a 1:1 line to represent agreement.

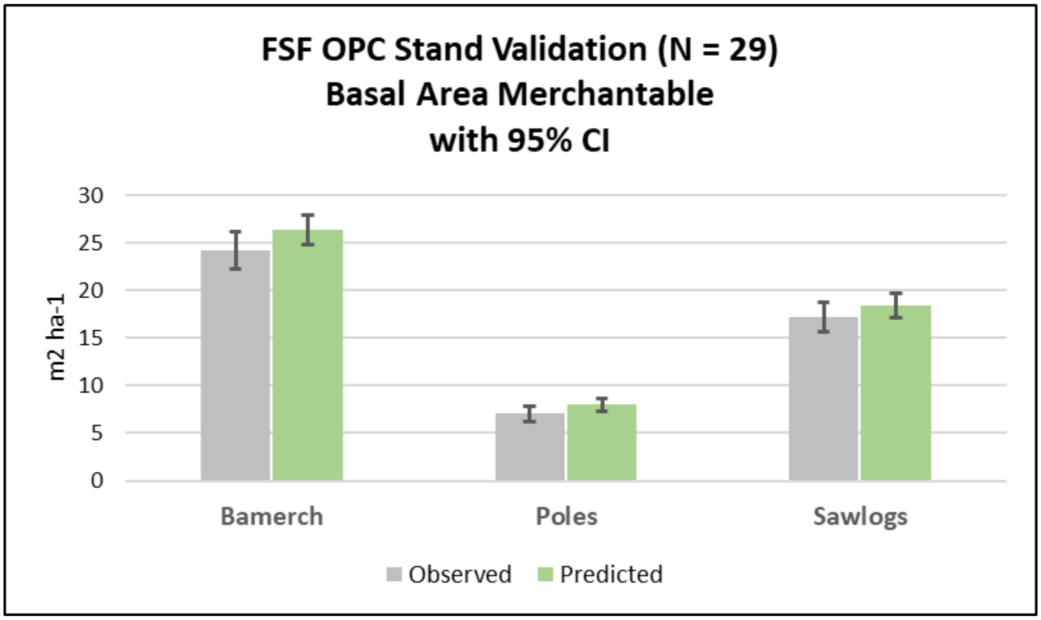


Figure 16 - Validation stand mean stand observed conditions and predictions. 95% Confidence intervals for observed and prediction are provided.

RMSE and Bias results for the 29 OPC cruised polygons (presented for All-Forest types and by Hardwood and by Pine) are presented in Table 13.

Table 13 - Validation RMSE and Bias results for the 29 OPC cruised polygons.

	N		Bamerch	Poles	Sawlog
All-Forest Types	**29**	**RMSE**	3.9	2.0	2.6
		RMSE %	16%	29%	15%
		Bias	-2.1	-0.9	-1.2
		Bias %	-9%	-13%	-7%
Hardwoods	**23**	**RMSE**	3.4	1.8	2.6
		RMSE %	14%	25%	15%
		Bias	-1.5	-0.5	-1.0
		Bias %	-6%	-7%	-6%
Pine	**6**	**RMSE**	5.3	2.7	2.8
		RMSE %	22%	41%	16%
		Bias	-4.6	-2.3	-2.3
		Bias %	-19%	-36%	-13%

Examples of individual hardwood and pine stand OPC observations and LiDAR predictions are presented in Figure 19.

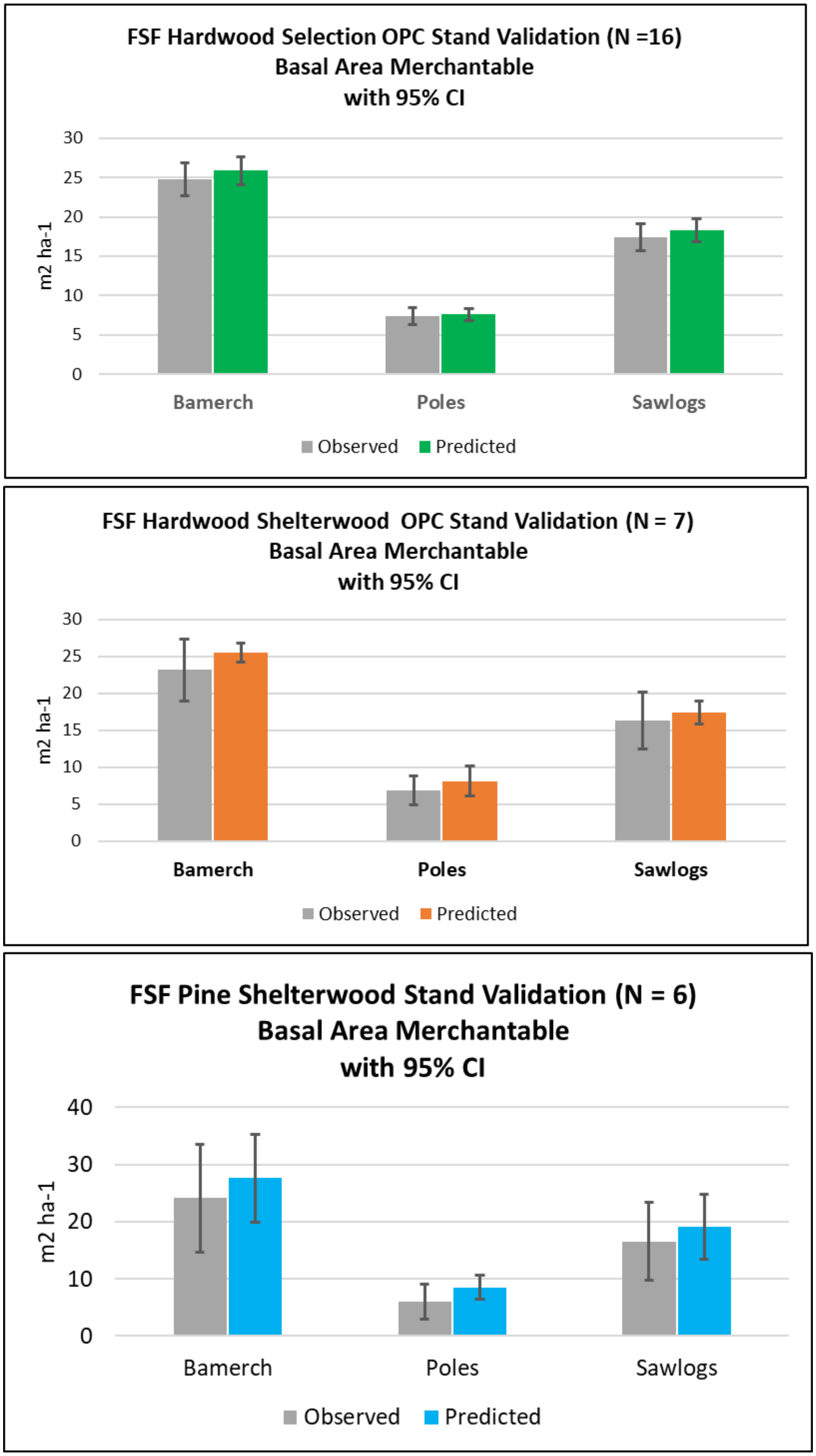


Figure 17 - - Validation stand mean stand observed conditions and predictions by forest type and silvicultural system. 95% Confidence intervals for observed and prediction are provided

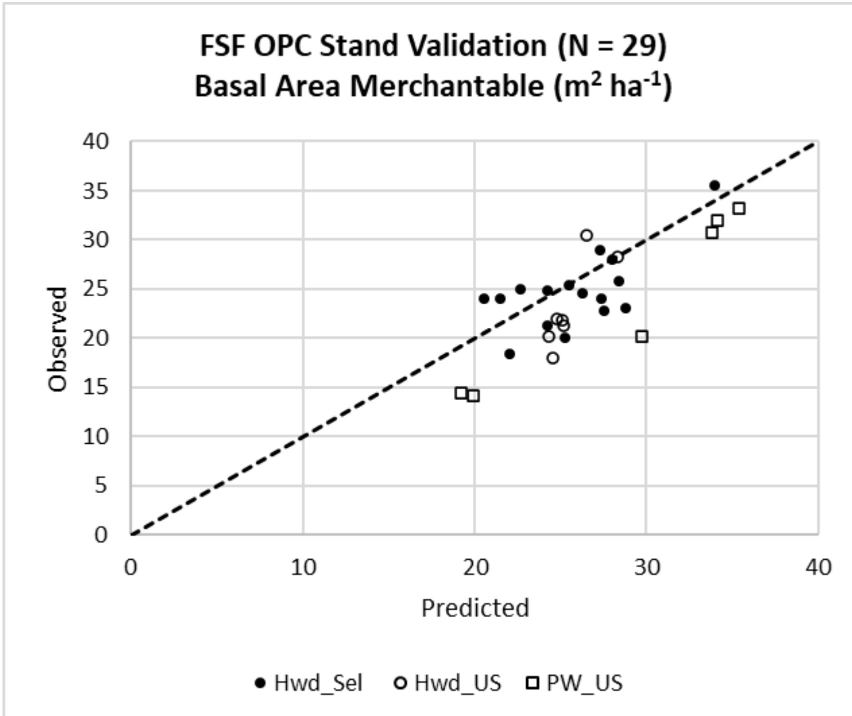


Figure 18 - FSF OPC Validation stand predictions versus observed by forest type.

T2 Inventory Updating

LiDAR Raster updating

The T2 inventory polygon update began with the Operational Planning Inventory (OPI) provided by Westwind Forest Stewardship SFL. This was updated to 2019. The T1 polygon boundaries were used and mean raster values by T1 polygon are calculated and provided for the following attributes:

- **Heights** - TopHt, CDHT, LoreyHt
- Basal Area,
- Stems
- **Volumes** – GMV_NL, GMV_WL, GMV_NL , FSF_Smlog
- **By Size Class** – Basal Area, GMV_NL
- QMD is calculated for each polygon based on mean stand Basal Area and Stems

Stand Level GMV_NL Quantiles

To provide a measure of stand level volume variation, the 15th and 85th quantiles of gross merchantable (NL) volume were also provided (GMV_NL_15 and GMV_NL_85).

An example of a raster prediction for GMV_NL and the corresponding mean polygon information are presented in Figure 20. Note how within stand variation of GMV_NL predictions are lost when the rasters are summarized for their mean value by polygon. The addition of Q15 and Q85 values allows

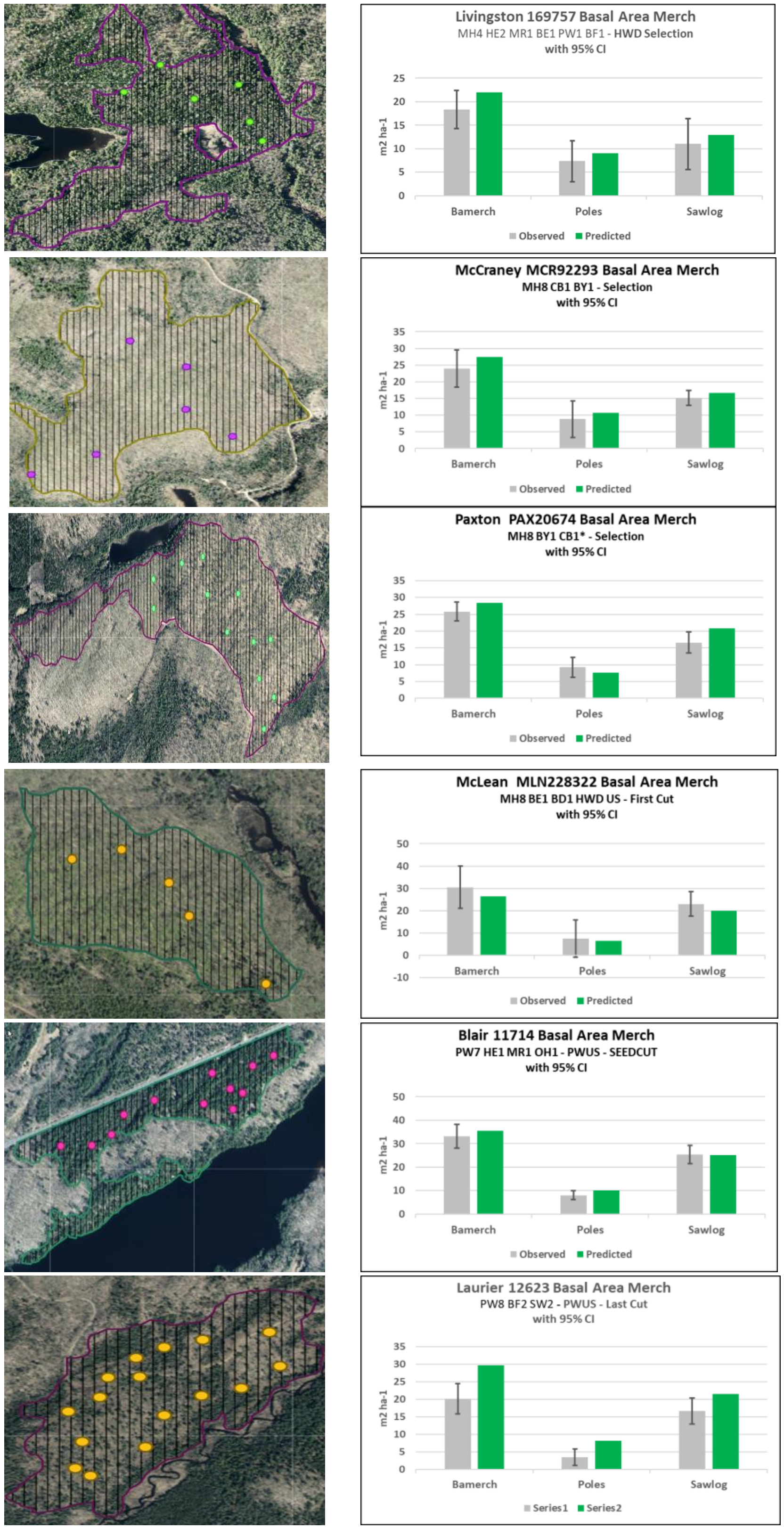


Figure 19 - Examples of individual stand observations and predicted values of merchantable basal area and basal area by pole and sawlog size class. The 95th confidence interval of the OPC is included.

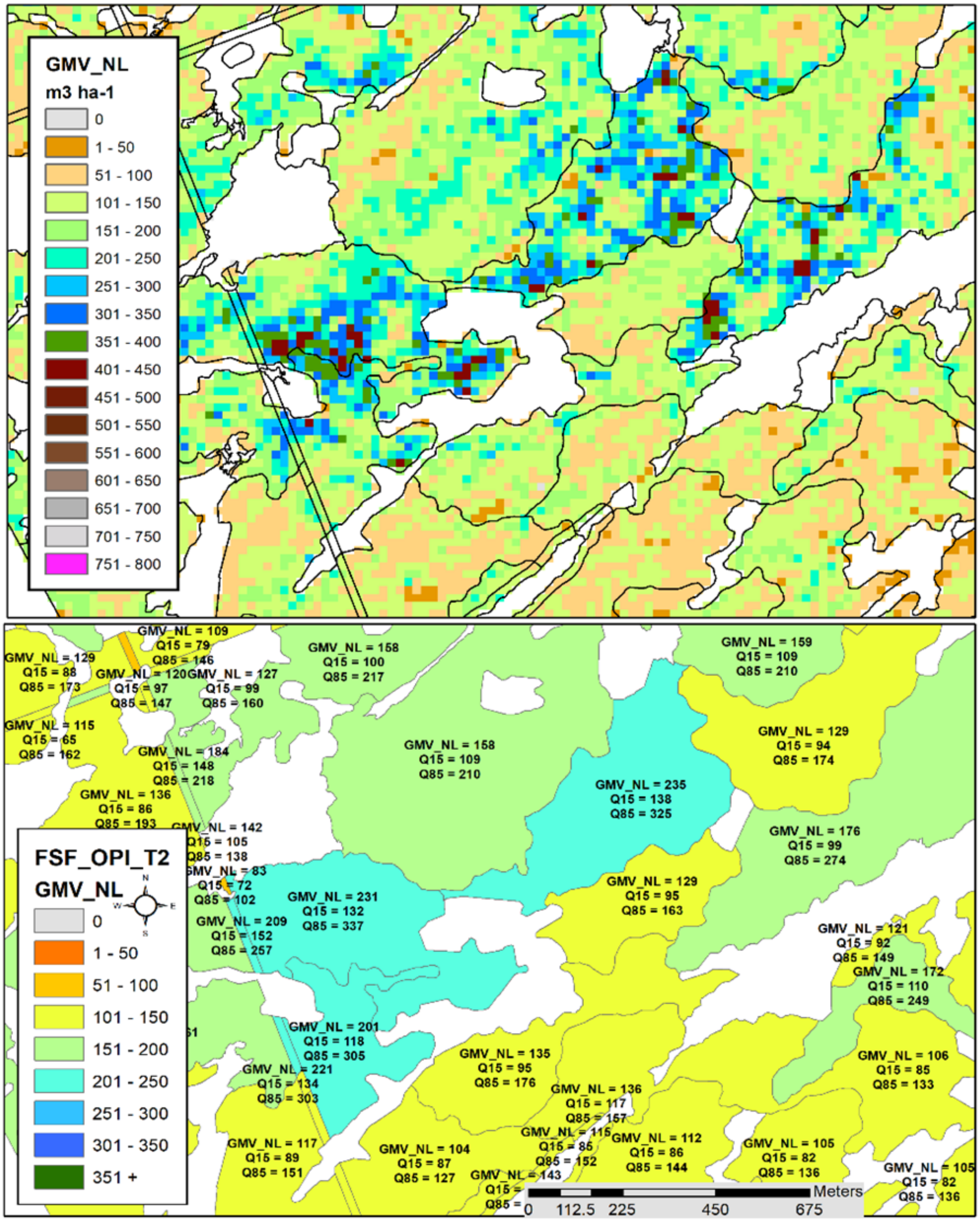


Figure 20 - Example of a GMV_NL (m3 ha-1) raster prediction and mean T2 Polygon summary. Mean GMV_NL (m3 ha-1) is labeled in each polygon along with the 15th and 85th quantile value. 70 percent of the GMV_NL is found between the quantile range.

The users of the inventory to also know that 70% of the GMV_NL pixels are between the Q15 and Q85 values for the polygon.

Huntsville Forest Products Gross Merchantable Volume (FSF_Smlog)

A request was made by Huntsville Forest Products (HFP) through Westwind Forest Stewardship Inc. for an additional gross merchantable volume calculation beyond the approved set of GMV_NL and GMV_WL described earlier. This additional volume would present LiDAR predictions for tolerant hardwood species (not including Ironwood) with a smaller upper diameter limit. The parameters specified are listed below.

- All hardwood species except Ironwood
- Minimum top diameter outside bark: 15 cm (6”)
- Maximum large end diameter outside bark: 60 cm (24”)
- Lengths of 259 cm (8’ 6”)

Note: in rare situations that the large end diameter of the bottom bolt is > 60 cm (24”), it is removed and the volume of the bolts above is calculated.

NOTE: The provided FSF_Smlog raster must be multiplied by the species composition of the tolerant hardwood species (except Ironwood) to calculate the hardwood volume to the HFP mill specifications.

Additional Attributes Calculated for T2 Inventory

To provide further value to the T2 update of the inventory, polygon-based summation (mean) of LiDAR attributes, were used in conjunction with T1 polygon age and species composition to calculate the following additional T2 inventory attributes:

- Site Index
- Stocking
- Cull Fraction
- Net Merchantable Volume (NMV).

Refer to Table 14 for a list of attributes and their source.

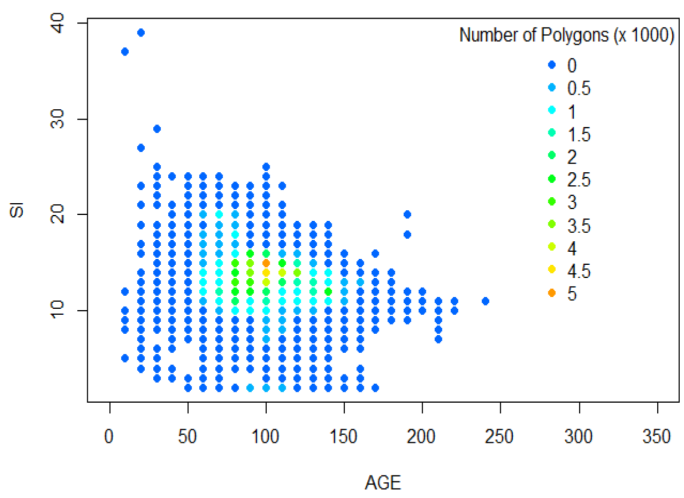
Table 14 - Additional T2 calculated inventory attributes and their source.

Attribute	LiDAR Derived	Calculated	T1 Polygon Information	Literature Source
Site Index	CDht		Age, Leading Species	Various (See Appendix D)
Stocking	Basal Area	Site Index	Age, Leading Species	Plonski 1974
Cull Fraction		VBAR, Site Index	Age, Species Composition	Basham 1991
Net Merchantable Volume	Basal Area , GMV_NL	Cull Fraction Species VBAR	Age, species composition	

Site Index

Site index is calculated using the leading species from the T1 species composition and the age from the T1 inventory updated to 2021 and the predicted LiDAR CDht. **For polygons with p99 < 5m, SI and stocking are not estimated.**

Most SI equations use breast height age. For young stands, small change in age result in large changes in SI. The SI estimates for young ages are unstable (Figure 21). The inventory age, particularly for young stands, may come from supplementary information and may not correspond to the LiDAR heights. This issue is illustrated for the FSF.



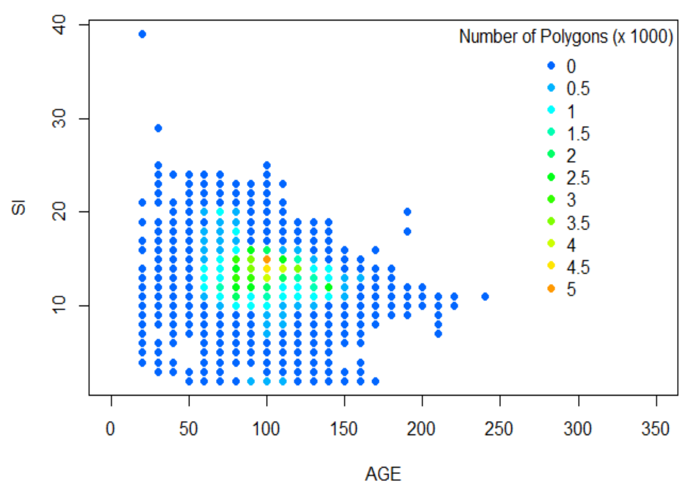


Figure 21 - Site index is plotted against age for ages 10+ (upper graph) and for ages 20+ (lower graph) for the FSF. Note the minimum SI is set to 5m and maximum at 35m.

Based on Figure 21, the SI for ages < 20 was set to missing and the SI for ages >= 20 was capped at 35m. The minimum SI was set to 5m. There are some potential issues with SI. For older stands, there may be a mismatch with age and height. The age is likely the age since disturbance and the heights are likely from younger trees that may have been established years after the disturbance.

Stocking

Stocking was calculated from predicted LiDAR basal area and the T1 polygon age and leading species. Stocking is in reference to Plonski's Normal Yield Table (Plonski 1974). Stocking is also a challenge for young stands. Stocking requires SI and SI was set to missing for stands < 20 years old so stocking is also not calculated when age is < 20. Stocking was capped at 2. Figure 22 provides a graphic of the number of FSF polygons by stocking and age. Note that stands less than 20 years old are not presented.

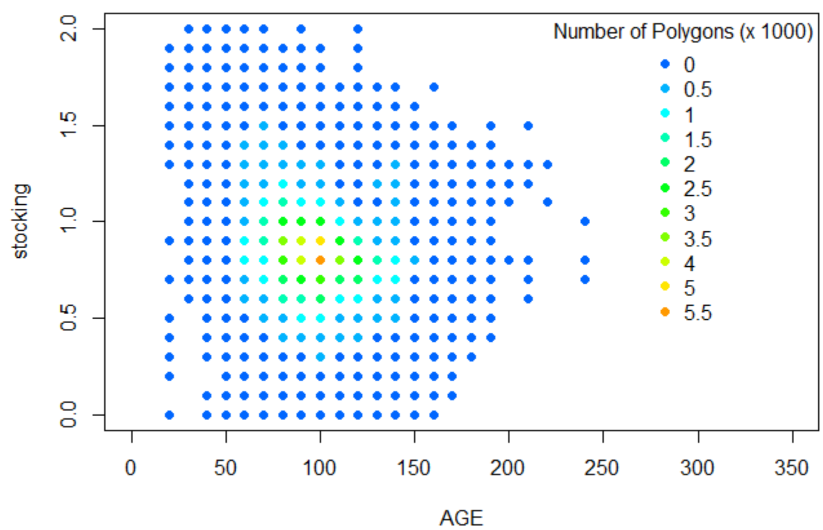


Figure 22 - Calculated Plonski stocking by polygon for the FSF. Note: no stocking estimates for stands < 20 years old.

Cull and Cull Fraction

Cull as estimated following the procedure implemented in MIST. Gross merchantable volume is estimated without respect to species. However, Net merchantable volume (NMV) requires estimates of cull. Basham (1991) provides estimates of cull by species and age.

First, a cull model ((1)) was fit, by species, using published data (see Table 15). The model predicts the cull fraction increases as a sigmoidal function of age.

$$(1) \qquad \widehat{cull} = (1 - e^{-d_0 \cdot age})^{d_1}$$

Where, $\widehat{cull}$ is the estimate of cull as a percentage of tree volume at a given age.

To apply this to GMV, the GMV by species was estimated by fitting a volume to basal area ratio (vbar) prediction model ((2)) by species using the provincial PSP/PGP database (gyPSPPGP_2021_10_04.bak).

$$(2) \qquad vbar = (v_0 + v_1 \cdot SI) \cdot \left(1 - e^{-v_2 \cdot age^{v_3}}\right)$$

Where, *vbar* is the volume to basal area ratio for a species, *SI* is the site index, *age* is the Plot age and v_0, v_1, v_2, and v_3 are coefficients.

The vbar estimate was used to estimate the relative GMV by species.

$$(3) \qquad mvol\ frac_i = \frac{species\ fraction_i \cdot vbar_i}{\sum species\ fraction_i \cdot vbar_i}$$

Table 15 - The sources for the cull estimates are given. The table references are from Basham (1991) except for red pine.

Species	Table	Comment
Hemlock	Table 7	
Sugar Maple	Table 13	
Yellow birch	Table 12	
Red pine		Source unknown. Basham (1991) reports an average of 1% for the 141-160 age class.
White pine	Table 1	
Cedar	Table 8	
White birch	Table 11	
Trembling aspen	Table 9	
Ironwood	Table 20	
Basswood	Table 16	
Balsam fir	Table 6	
White elm	Table 19	
Red oak	Table 18	
Black ash	Table 17	
Beech	Table 15	
Red maple	Table 14	
White spruce	Table 5	Note that the data for age 170 was taken from Table 6 of OMNR (1978)
Jack pine	Table 2	
Black spruce	Table 4	Note that data from ages 200+ were not used

Then the weighted cull estimate, all species combined, is estimated as follows.

$$(4) \qquad cull = \sum mvol\ frac_i \cdot spp\ cull\ est_i$$

Sample calculations are given in Table 16. An example of vbar estimates by age and species is presented in Figure 23.

Table 16 - Vbar and cull calculations are given for sample conditions. The age = 100 and SI = 20m. Poplar has a slightly higher vbar, giving slightly more weight to the poplar cull estimate.

	Spp	Vbar coefficient					Cull coefficient			Mvol	weighted
Spp	frac	V0	V1	V2	V3	Vbar	D0	D1	cull	frac	cull
Pj	0.8	2.36509	0.54016	0.018021	1.01063	11.2	-0.01264	8.3752	0.062	0.79	0.049
Po	0.2	2.99849	0.50008	0.006109	1.30665	11.9	-0.00521	1.4052	0.282	0.21	0.059
All											0.108

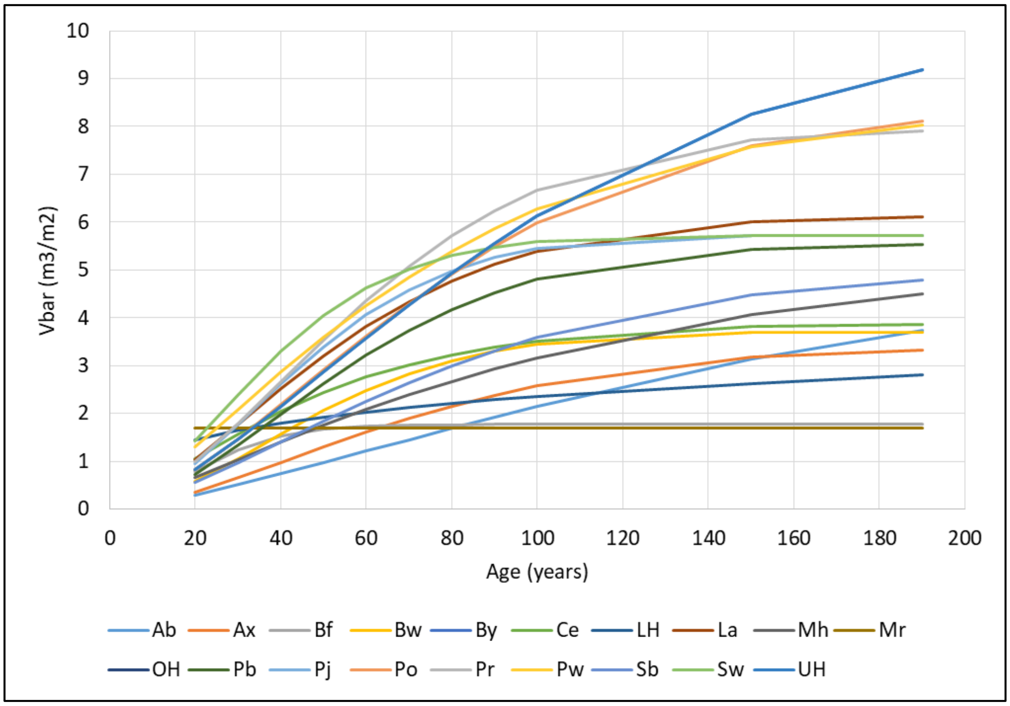


Figure 23 - The vbar estimates are given by age and species, for SI = 20

Net Merchantable Volume

For the T1 polygons, cull was estimated at using the T1 age and species composition.

Net merchantable volume (NMV) is calculated as the GMV minus cull.

$$(5) \qquad NMV = \text{GMV} \cdot (1 - cull)$$

Constraint of T2 Inventory Updates

Only trees ≥ 7.1 cm were measured on all the calibration plots. As a result, shorter (and young) stands do not have any measured trees to support defensible LiDAR predictions. **Stands < 20 years are not being updated with LiDAR derived predictions and are set to <NULL>.** In addition, different polygon CDHT thresholds were used to constrain provided inventory attributes (Table 17). Crown Closure (CC2m) was retained for all stands. If stand CDHT <5 m, zq99 replaced estimated CDHT value.

Table 17 - T2 polygon inventory attributes and instituted constraints for all stands with age ≥ 20 years

	Polygon CDHT <5m	**Polygon 5m > CDHT <9m**	**Polygon CDHT >9m**
CC2m			
CC10m			
TOPHT	NULL		
CDHT	Zq99		
LoreyHT	NULL		
BA	0		
BAmerch	0	0	
Stems	0		
QMD	NULL		
GTV	0	0	
GMV_NL	0	0	
GMV_WL	0	0	
GMV_Util	0	0	
NMV_NL	0	0	
NMV_WL	0	0	
Biomass	0	0	
BA_Poles	0	0	
BA_SmSaw	0	0	
BA_MedSaw	0	0	
BA_LgSaw	0	0	
GMV_Poles	0	0	
GMV_SmSaw	0	0	
GMV_MedSaw	0	0	
GMV_LgSaw	0	0	
FSF_Smlog	0	0	
Site Index	NULL		
Stocking	NULL		
Cull Fraction	NULL	NULL	

Discussion

Calibration Plot Data Quality

Concern about calibration plot data quality has been expressed earlier. Although an attempt was undertaken to adjust tree heights due to observed field measurement errors, other potential sources of measurement error (i.e., target plot location not being achieved, DBH measurement, missed trees, etc.) could not be evaluated or adjusted for in compilation. The assumption had to be made that the other tree attributes were done well. However, a level of concern exists on the unknown impact of the field plot data quality and the results reported. **FRI quality is directly linked to field plot quality. Audits of field plots should occur as soon as data collection begins in order to identify and correct any data collection issues as quickly as possible.**

Plot Level Model Validation (CV)

Overall, the FSF pixel level predictions are like those reported in other studies in Ontario. White et al. (2021) reported results for similar forest types and SPL. In their work, larger calibration plots (625m2) were used and a lower Dbh measurement threshold (2.5cm vs. 7.1cm used in this study) was chosen. They reported RF Out-of-Bag (OOB) RMSE errors which are comparable to the CV RMSE error statistics reported here. White et al. (2021) reported RMSE of 15% for CDHT for All-Forest types. We report a similar RMSE of 10%. For volumes, White et al. (2021) reported 25.4% and 29.6% for basal area and GTV. This study reported slightly higher results of 29% and 33%. In White et al.'s (2021) work they reported a similar total above ground biomass RMSE of 25% vs our reported 30%. The work of White et al. (2021) had an additional 80 calibration plots versus what was available to use for modeling on the FSF.

Recent inventory efforts on the Algonquin Park Forest and SPL ABA estimates found comparable (but slightly higher) RMSE results. This may be partly due to the fact that the same contractor with the noted data quality issues was involved in collecting the calibration field data for both forests and the FSF being their first forest of their contract. Results from the APF reported RMSE's of 12%, 23%, 25% and 23% for All-Forest type CDHT, Basal Area, GTV and Biomass.

Where possible to broadly compare forest units (criteria differ but leading species is similar) we found the following. White et al. (2021) reported Tolerant Hardwood stand RMSEs for CDHT, Basal Area, GTV and biomass of 8%, 31%, 38% and 27% respectively. This study found similar or better results (likely partly due to a higher minimum Dbh threshold) in the Tolhwd of 10%, 29%, 29% and 27%. White pine was reported as managed/natural stands in the work of White et al. (2021). They reported 12%/19%, 20%/26%, 26%/ 27%, and 21%/26% for CDHT, Basal Area, GTV and biomass respectively. This study reported on a combined managed and natural Pine stand grouping at 9%, 30%, 35% and 33%. While the Tolhwd group performed better than the study of White et al. (2021) the Pine group generally performed poorer.

A comparison of the RMSE's between the APF and FSF results for these same two forest types found similar trends. RMSE's of 10%, 21%, 23%, and 23% were reported for APF Tolhwd CDHT, Basal Area, GTV and biomass. For Pine, RMSE's of 13%, 23%, 25% and 23% respectively were noted from the APF modeling results. Generally, FSF model RMSE results for Tolhwds were similar to those reported for APF.

However, RMSE results for the Pine forest type on the FSF were poorer than both the work of White et al (2021) and those found for the APF inventory effort. This finding may be a function of calibration data quality or the reduced number of Pine plot observations available to help train the model on the FSF (White et al. (2021) – 107 plots, APF – 82 plots, FSF – 46 plots).

Stand/Block Level Model Validation

As has been demonstrated in other published LiDAR inventory projects (White et al. 2021), validation of LiDAR predictions is more appropriately evaluated at the scale at which most management decisions are based. In Ontario, this is generally the harvest block or stand level.

Although the validation sample of 29 stands on the FSF is not large and only focuses on two forest types, it can still provide a sense of expected model performance at the appropriate scale for an inventory. It should be reiterated that the field validation sampling on the FSF was not an intensive (not a fixed grid of plots covering the extent of the stand) LiDAR validation effort but an opportunistic dataset representing OPC results of stands intended to develop harvesting prescriptions. As such, some of the plot locations were focused on the species or site conditions being managed and as a result, the OPC results too are also a stand level estimate of what and where they cruised. We are very grateful to the efforts of the Westwind Stewardship Forest staff for making these data available to this project.

Calculating the sampling intensity is challenging for variable radius plots but if the plots were 0.04ha, the approximate sampling intensity was 1.3% (range of 0.6% -3.4%) or 3.6 ha being sampled by each plot (Table 12).

OPC data collection focused on the measurement and size-characterization of merchantable basal area. The All-Forest type RMSE for BAmerch dropped from 30% (at the plot/grid cell scale) to 16% at the stand scale. When analyzed by FT, Tolhwd (N=23) had better results (RMSE = 14%) when compared with the fewer Pine stands assessed (N=6) reporting an RMSE of 22%. Figure 24 graphically displays this comparison of 400m^2 scale error versus stand level. However, as expected RMSE at the stand scale decreased.

Challenges with aligning and summarizing vector data and raster data

T1 information in the inventory is polygon based, including species composition and forest classification (forest vs. non forest). LiDAR derived information in pixel based. An issue arises when aligning the two sources of information. T1 polygon boundaries do not follow raster edges and, as a result, bisect pixels.

Since, currently in Ontario, forests are managed at the polygon level, approaches to summarizing raster values within polygons was explored.

Two main approaches investigated for operational inventory production are discussed here.

1. Centroid based zonal summation
2. Area-weighted based summation

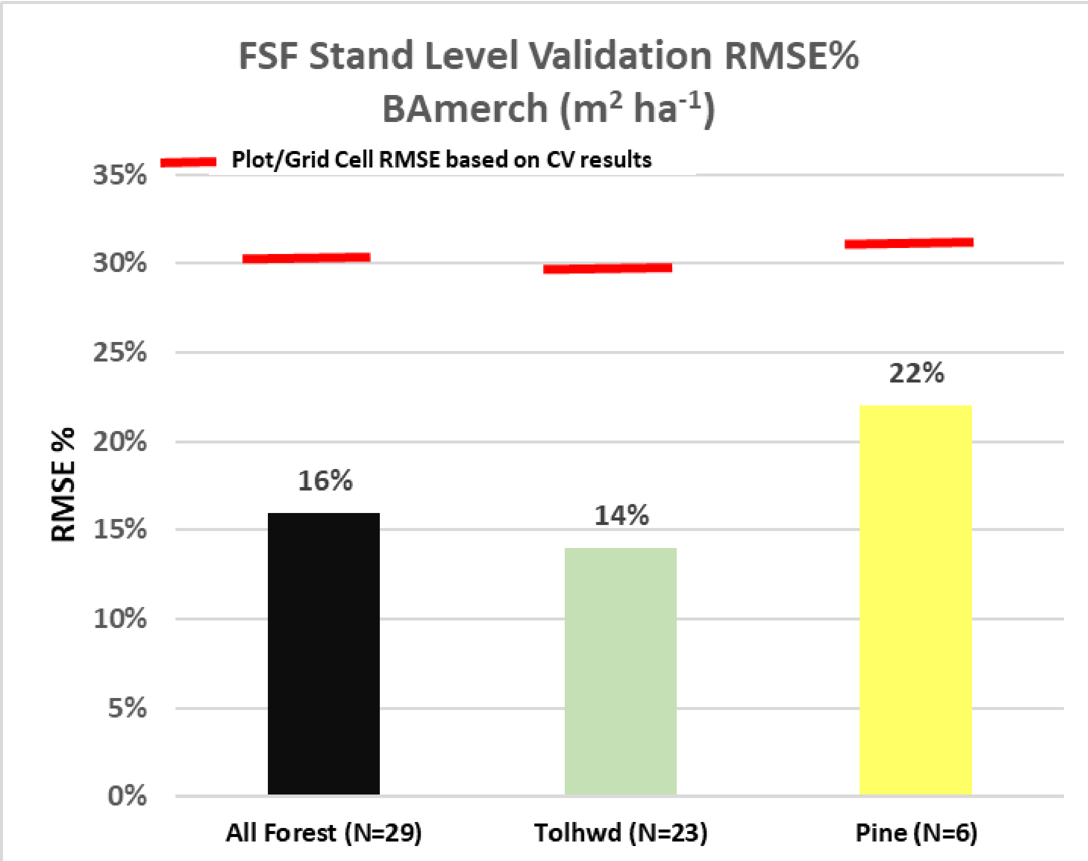


Figure 24 - Comparison of Stand level validation RMSE with Cross Validation RMSE at the plot/grid cell scale for All- Forest, Tolhwd and Pine BAmerch.

Some tools provide polygon summaries from raster layers by only selecting raster pixels with centroids within the polygon. This can result in edge raster pixels being excluded if they border linear features such as roads/rivers, water bodies (Figure 25) and the centroid is in that feature. In addition, where polygons bisect raster pixels, only one polygon is assigned the value of the raster pixel (

Figure 26). The issue is particularly problematic for small polygons (< 1 ha).

In an area-weighted approach, the pixel's contribution to a polygon is weighted by the portion of the pixel falling within a polygon. This means a pixel can potentially be part of more than one polygon.

Pixels that fall entirely within the polygon will have a weight of one. If half of a pixels falls within a polygon, the pixel will be given a weight of 0.5.

The decision to implement the area-weighted approach to generating T2 polygon raster summaries was selected. This method ensured that each polygon benefits from an appropriately weighted proportion of each raster pixel covered by the polygon.

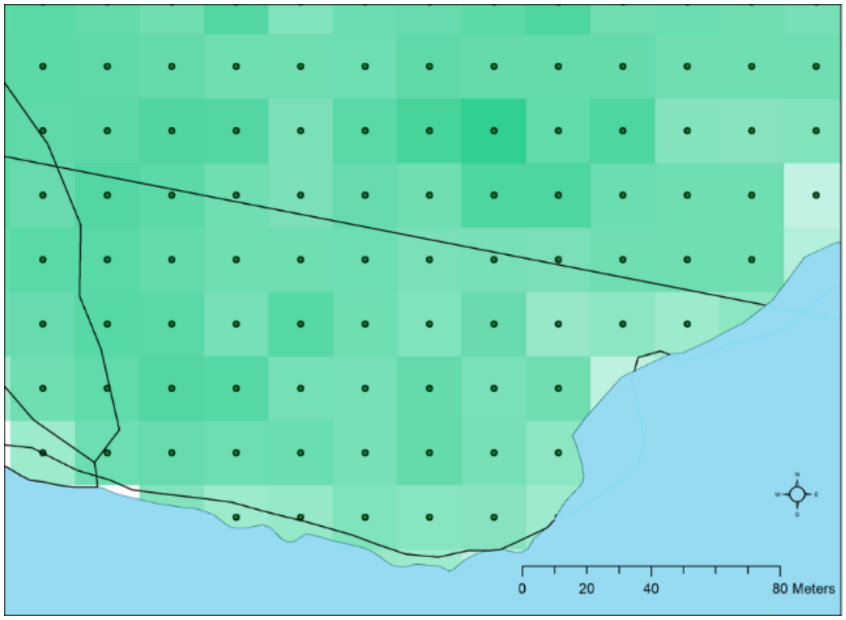


Figure 25 - Example of centroid selection or raster cells excluding raster values for narrow polygons along waterbodies.

Figure 26 - Example of a raster pixel being bisected into 4 by polygon boundaries with only one polygon including the centroid value.

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Appendix A - LiDAR predictors for FSF- SPL–2018

Full point cloud predictor suite derived from LidR software scripts from a threshold height > 0 m unless specified. Predictors selected for use in Random Forest modeling of inventory attributes are shaded.

Attribute	Threshold	Description	Model Predictor
zmax	>0m	max height of z	
zmean	>0m	mean height of z	
zsd	>0m	standard deviation of z	
zskew	>0m	skewness of z	
zkurt	>0m	kurtosis of z	
zentropy	>0m	entropy of height distribution (z)	
pzabovezmean	>0m	percentage of returns above zmean	
pzabove0	>0m	percentage of returns above threshold	
zq5	>0m	height of the 5th percentile of z	
zq10	>0m	height of the 10th percentile of z	
zq15	>0m	height of the 15th percentile of z	
zq20	>0m	height of the 20th percentile of z	
zq25	>0m	height of the 25th percentile of z	
zq30	>0m	height of the 30th percentile of z	
zq35	>0m	height of the 35th percentile of z	
zq40	>0m	height of the 40th percentile of z	
zq45	>0m	height of the 45th percentile of z	
zq50	>0m	height of the 50th percentile of z	
zq55	>0m	height of the 55th percentile of z	
zq60	>0m	height of the 60th percentile of z	
zq65	>0m	height of the 65th percentile of z	
zq70	>0m	height of the 70th percentile of z	
zq75	>0m	height of the 75th percentile of z	
zq80	>0m	height of the 80th percentile of z	
zq85	>0m	height of the 85th percentile of z	
zq90	>0m	height of the 90th percentile of z	
zq95	>0m	height of the9 5th percentile of z	
zq99	>0m	height of the 99th percentile of z	
zpcum1	>0m	percent of z returns below the 1st decile	
zpcum2	>0m	percent of z returns below the 2nd decile	
zpcum3	>0m	percent of z returns below the 3rd decile	
zpcum4	>0m	percent of z returns below the 4th decile	
zpcum5	>0m	percent of z returns below the 5th decile	
zpcum6	>0m	percent of z returns below the 6th decile	
zpcum7	>0m	percent of z returns below the 7th decile	
zpcum8	>0m	percent of z returns below the 8th decile	
zpcum9	>0m	percent of z returns below the 9th decile	
zsd95	>0m	standard deviation of z trimmed to 95%	
zskew95	>0m	skewness of z trimmed to 95%	
zkurt95	>0m	kurtosis of z trimmed to 95%	
zmin	>0m	minimum height of z returns	
allpts	>=0m	count of all points > Threshold (2,3,4,5)	
allptsAT	>0m	count of all points (2,3,4,5)	
vegcnt	>=0m	count of vegetation points (3,4,5)	
firstveg	>=0m	count of first return points of vegetation (3,4,5)	
firstcnt	>=0m	count of first returns	
firstonlycnt	>=0m	count of first and ONLY return points of vegetation (3,4,5)	
groundcnt	>=0m	count of f=ground returns (2)	
vegratio	>=0m	vegetation ratio (vegetation points (vegcnt) / all points (allpts))	
da	>=0m	percentage of First Returns / all returns (firstcnt / allpts) *100	
db	>=0m	percentage of "First & Only" Returns / all returns (firstonlycnt	
dv	>=0m	percentage of "Vegetation & Only" Returns / all returns	
vdr	>0m	Vertical Distribution Ratio (max-median)/max	
cv	>0m	coefficient of variation of z returns	

vci_1m	>0m	vegetation complexity index - 1m bins (Van Ewijk 2011)	
cov_2m	NA	canopy cover % above 2m (number of first returns above 2m / number of first returns) * 100	
cov_4m	NA	canopy cover % above 4m (number of first returns above 4m / number of first returns) * 100	
cov_6m	NA	canopy cover % above 6m (number of first returns above 6m / number of first returns) * 100	
cov_8m	NA	canopy cover % above 8m (number of first returns above 8m / number of first returns) * 100	
cov_10m	NA	canopy cover % above 10m (number of first returns above 10m / number of first returns) * 100	
cov_12m	NA	canopy cover % above 12m (number of first returns above 12m / number of first returns) * 100	
cov_14m	NA	canopy cover % above 14m (number of first returns above 14m / number of first returns) * 100	
cov_16m	NA	canopy cover % above 16m (number of first returns above 16m / number of first returns) * 100	
cov_18m	NA	canopy cover % above 18m (number of first returns above 18m / number of first returns) * 100	
cov_20m	NA	canopy cover % above 20m (number of first returns above 20m / number of first returns) * 100	
cov_22m	NA	canopy cover % above 22m (number of first returns above 22m / number of first returns) * 100	
cov_24m	NA	canopy cover % above 24m (number of first returns above 24m / number of first returns) * 100	
cov_26m	NA	canopy cover % above 26m (number of first returns above 26m / number of first returns) * 100	
cov_28m	NA	canopy cover % above 28m (number of first returns above 28m / number of first returns) * 100	
cov_30m	NA	canopy cover % above 30m (number of first returns above 30m / number of first returns) * 100	
cov_32m…	NA	canopy cover % above 32m (number of first returns above 30m / number of first returns) * 100	
dns_2m	NA	canopy cover % above 2m (number of all returns above 2m / number of all returns) * 100	
dns_4m	NA	canopy cover % above 4m (number of all returns above 4m / number of all returns) * 100	
dns_6m	NA	canopy cover % above 6m (number of all returns above 6m / number of all returns) * 100	
dns_8m	NA	canopy cover % above 8m (number of all returns above 8m / number of all returns) * 100	
dns_10m	NA	canopy cover % above 10m (number of all returns above 10m / number of all returns) * 100	
dns_12m	NA	canopy cover % above 12m (number of all returns above 12m / number of all returns) * 100	
dns_14m	NA	canopy cover % above 14m (number of all returns above 14m / number of all returns) * 100	
dns_16m	NA	canopy cover % above 16m (number of all returns above 16m / number of all returns) * 100	

dns_18m	NA	canopy cover % above 18m (number of all returns above 18m / number of all returns) * 100	
dns_20m	NA	canopy cover % above 20m (number of all returns above 18m / number of all returns) * 100	
dns_22m	NA	canopy cover % above 22m (number of all returns above 18m / number of all returns) * 100	
dns_24m	NA	canopy cover % above 24m (number of all returns above 24m / number of all returns) * 100	
dns_26m	NA	canopy cover % above 26m (number of all returns above 26m / number of all returns) * 100	
dns_28m	NA	canopy cover % above 28m (number of all returns above 28m / number of all returns) * 100	
dns_30m	NA	canopy cover % above 30m (number of all returns above 30m / number of all returns) * 100	
dns_32m…	NA	canopy cover % above 32m (number of all returns above 30m / number of all returns) * 100	
vegden_0_2	>=0m	Percent vegetation returns between 0 and 2m	
vegden_2_4	>=0m	Percent vegetation returns between 2 and 4m	
vegden_4_6	>=0m	Percent vegetation returns between 4 and 6m	
vegden_6_8	>=0m	Percent vegetation returns between 6 and 8m	
vegden_8_10	>=0m	Percent vegetation returns between 10 and 10m	
vegden_10_12	>=0m	Percent vegetation returns between 10 and 12m	
vegden_12_14	>=0m	Percent vegetation returns between 12 and 14m	
vegden_14_16	>=0m	Percent vegetation returns between 14 and 16m	
vegden_16_18	>=0m	Percent vegetation returns between 16 and 18m	
vegden_18_20	>=0m	Percent vegetation returns between 18 and 20m	
vegden_20_22	>=0m	Percent vegetation returns between 20 and 22m	
vegden_22_24	>=0m	Percent vegetation returns between 22 and 24m	
vegden_24_26	>=0m	Percent vegetation returns between 24 and 26m	
vegden_26_28	>=0m	Percent vegetation returns between 26 and 28m	
vegden_28_30	>=0m	Percent vegetation returns between 28 and 30m	
vegden_30_32	>=0m	Percent vegetation returns between 30 and 32m	
vegden_32_34	>=0m	Percent vegetation returns between 32 and 34m	
L1	NA	L1 moment of vegetation points (3,4,5)	
L2	NA	L2 moment of vegetation points (3,4,5)	
L3	NA	L3 moment of vegetation points (3,4,5)	
L4	NA	L4 moment of vegetation points (3,4,5)	
Lskew	NA	L Skewness of vegetation points (3,4,5)	
Lkurt	NA	L Kurtosis of vegetation points (3,4,5)	
Lcoefvar	NA	L Coeficient of Variation of vegetation points (3,4,5)	
ngrcnt	-0.15	count of all points (2,3,4,5) between -0.15 and 0.15 for LPI	
allptscnt_ngr	-0.15	Count of all points (2,3,4,5) between -0.15 and 48m for LPI	
lpi	-0.15	LiDAR penetration index - count of returns between (-0.15 - 0.15)/all points (-.15 to 30m) * 100 [Uses Class 2,3,4,5]	
ri_pts	NA	rumple index based on LiDAR points - 1m DSM	

Appendix B – Plot level validation statistics by CV methods

Ten-Fold Cross Validation Plot level model statistics by Forest Type

Top Ht		Observed			Prediction					
m	N	Mean	Min	Max	Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	21.0	17.3	24.4	20.7	0.6	1.4	6.7	0.3	1.4
HE	10	22.6	15.3	28.8	22.5	1.1	1.6	7.1	0.1	0.4
Intol	2	20.2	19.9	20.5	19.3	1.3	1.4	6.9	0.9	4.5
Low	8	15.6	10.8	26.3	17.1	2.1	2.3	14.7	-1.5	-9.6
MW	8	19.7	12.3	22.9	19.3	1.3	1.1	5.6	0.4	2.0
OAK	2	22.6	21.5	23.8	22.7	1.7	0.5	2.2	-0.1	-0.4
Pine	46	26.2	13.4	34.4	25.8	0.8	1.7	6.5	0.4	1.5
PJ	2	11.8	10.3	13.2	13.3	1.0	1.6	13.6	-1.6	-13.6
PR	15	26.2	17.3	33.5	25.8	1.0	1.0	3.8	0.4	1.5
SF	14	18.9	9.5	27.6	17.6	1.4	2.2	11.6	1.3	6.9
Tolhwd	75	21.9	13.2	30.7	22.1	0.4	1.4	6.4	-0.3	-1.4

CDHT		Observed			Prediction					
m	N	Mean	Min	Max	Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	18.7	15.8	22.7	19.0	0.6	1.3	7.0	-0.3	-1.6
HE	10	20.5	13.9	24.1	20.0	1.0	1.5	7.3	0.6	2.9
Intol	2	17.2	15.2	19.2	17.5	1.7	0.4	2.3	-0.3	-1.7
Low	8	14.0	9.1	21.4	15.2	2.0	2.5	17.9	-1.2	-8.6
MW	8	17.4	9.5	20.8	17.3	1.2	1.9	10.9	0.1	0.6
OAK	2	19.2	18.4	20.0	20.3	1.8	2.8	14.6	-1.0	-5.2
Pine	46	24.2	10.4	31.6	23.9	0.8	2.1	8.7	0.3	1.2
PJ	2	10.8	9.6	12.0	11.7	0.4	1.2	11.1	-0.9	-8.3
PR	15	25.3	17.0	32.9	24.4	1.0	2.0	7.9	0.9	3.6
SF	13	15.5	8.4	24.1	14.7	1.4	2.4	15.5	0.8	5.2
Tolhwd	75	19.7	10.7	28.3	19.9	0.4	1.9	9.6	-0.2	-1.0

Lorey's Ht		Observed			Prediction					
m	N	Mean	Min	Max	Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	19.3	16.6	21.8	18.8	0.5	1.1	5.7	0.5	2.6
HE	10	20.5	13.3	25.4	20.1	1.2	1.7	8.3	0.4	2.0
Intol	2	17.5	15.7	19.3	17.6	1.3	0.5	2.9	-0.1	-0.6
Low	8	14.4	9.9	22.7	14.9	1.8	1.7	11.8	-0.6	-4.2
MW	8	16.2	10.6	19.7	17.2	1.2	1.7	10.5	-1.0	-6.2
OAK	2	19.8	17.5	22.1	20.5	2.0	0.8	4.0	-0.7	-3.5
Pine	46	23.3	12.2	30.8	23.0	0.7	1.8	7.7	0.2	0.9
PJ	2	10.7	9.5	11.8	12.1	0.5	1.6	15.0	-1.5	-14.0
PR	15	24.9	17.0	31.5	23.7	1.0	1.8	7.2	1.1	4.4
SF	14	15.7	8.6	27.6	15.0	1.2	2.6	16.6	0.7	4.5
Tolhwd	75	19.8	10.8	27.9	20.0	0.4	1.4	7.1	-0.1	-0.5

QMD		Observed			Prediction					
cm	N	Mean	Min	Max	Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	23.5	18.7	30.6	23.4	0.9	3.8	16.2	0.1	0.4
HE	10	30.3	16.6	39.2	28.3	2.6	3.4	11.2	2.0	6.6
Intol	2	19.9	13.4	26.4	24.7	4.1	5.4	27.1	-4.8	-24.1
Low	8	16.7	9.3	25.1	19.9	2.3	6.8	40.7	-3.2	-19.2
MW	8	18.9	12.5	27.2	20.3	1.6	3.9	20.6	-1.3	-6.9
OAK	2	24.7	19.7	29.6	25.5	2.1	3.0	12.1	-0.9	-3.6
Pine	46	27.7	14.2	69.3	25.9	0.9	7.0	25.3	1.8	6.5
PJ	2	14.6	14.3	14.8	16.7	0.3	2.2	15.1	-2.1	-14.4
PR	15	30.0	19.2	68.7	29.7	1.5	8.4	28.0	0.3	1.0
SF	14	16.4	10.5	30.5	20.5	2.4	7.5	45.7	-4.1	-25.0
Tolhwd	75	23.1	12.6	37.9	23.3	0.5	3.5	15.2	-0.2	-0.9

BasalArea		Observed			Prediction					
$m^2 ha^{-1}$	N	Mean	Min	Max	Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	26.1	16.3	29.4	29.4	1.1	4.4	16.9	-3.3	-12.6
HE	10	41.2	10.3	52.7	38.4	4.1	9.0	21.8	2.8	6.8
Intol	2	29.0	27.8	30.2	42.0	6.0	13.9	47.9	-13.0	-44.8
Low	8	16.2	1.2	39.8	15.7	2.7	8.3	51.2	0.4	2.5
MW	8	28.2	10.2	51.8	25.8	2.2	10.7	37.9	2.4	8.5
OAK	2	32.0	24.4	39.6	26.8	7.0	5.2	16.2	5.1	15.9
Pine	46	27.5	2.2	96.4	27.0	2.2	8.3	30.2	0.5	1.8
PJ	2	12.9	11.7	14.2	14.0	1.7	1.1	8.5	-1.0	-7.8
PR	15	33.7	9.3	68.9	31.6	4.0	8.2	24.3	2.0	5.9
SF	14	19.2	0.5	53.5	18.7	2.9	4.0	20.8	0.5	2.6
Tolhwd	75	23.9	9.5	45.6	24.9	0.6	6.9	28.9	-1.0	-4.2

BasalArea merch		Observed			Prediction					
$m^2 ha^{-1}$	N	Mean	Min	Max	Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	25.5	15.6	29.1	28.7	1.0	4.0	15.7	-3.1	-12.2
HE	10	40.9	9.7	52.2	38.7	4.7	10.7	26.2	2.2	5.4
Intol	2	27.5	24.7	30.2	41.9	5.3	14.6	53.1	-14.4	-52.4
Low	8	15.3	0.4	36.7	15.0	2.7	7.7	50.3	0.3	2.0
MW	8	27.2	8.8	50.7	25.3	2.4	11.2	41.2	1.8	6.6
OAK	2	31.6	23.6	39.6	25.4	6.4	6.4	20.3	6.2	19.6
Pine	46	26.9	2.2	95.0	26.5	2.2	8.1	30.1	0.4	1.5
PJ	2	12.6	11.2	14.0	12.4	0.8	0.7	5.6	0.3	2.4
PR	15	33.2	9.3	67.4	31.3	3.8	7.7	23.2	1.9	5.7
SF	14	17.5	0.5	53.5	17.2	2.9	4.2	24.0	0.3	1.7
Tolhwd	75	23.2	8.2	43.9	24.4	0.6	7.1	30.6	-1.1	-4.7

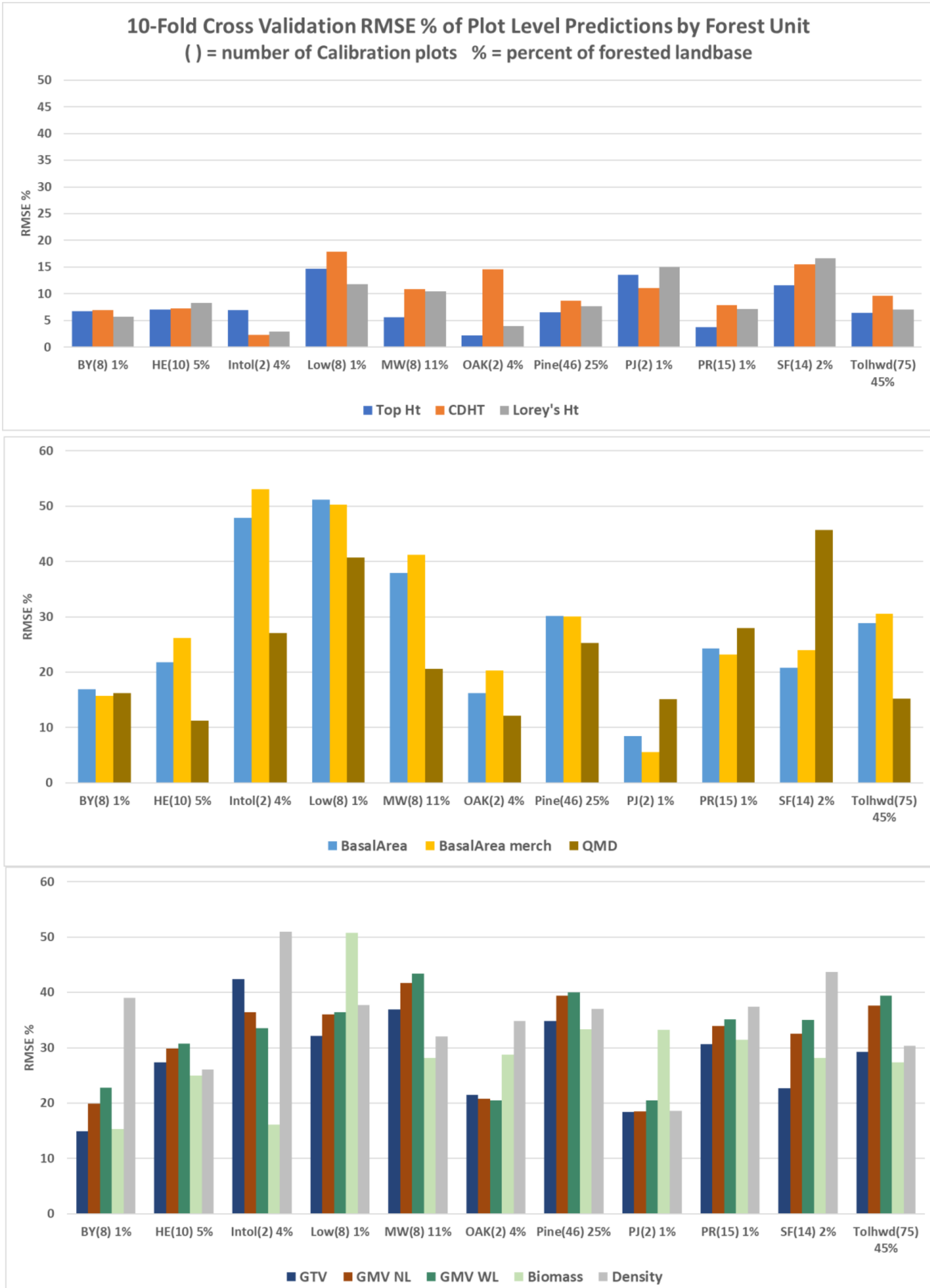
GTV		Observed			Prediction					
$m^3 ha^{-1}$	N	Mean	Min	Max	Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	197.6	120.4	225.9	220.8	10.5	29.4	14.9	-23.1	-11.7
HE	10	306.7	53.4	435.8	310.4	41.5	84.1	27.4	-3.7	-1.2
Intol	2	214.1	189.4	238.9	299.8	54.6	90.7	42.4	-85.7	-40.0
Low	6	129.4	49.7	266.9	136.5	28.8	41.5	32.1	-7.1	-5.5
MW	8	200.5	46.4	397.9	184.3	21.8	74.0	36.9	16.2	8.1
OAK	2	276.8	185.5	368.1	220.7	71.7	59.4	21.5	56.0	20.2
Pine	46	276.0	15.7	1055.1	265.8	25.4	96.0	34.8	10.2	3.7
PJ	2	61.3	47.7	75.0	72.7	13.9	11.3	18.4	-11.3	-18.4
PR	15	377.1	109.3	855.9	320.5	44.8	115.4	30.6	56.6	15.0
SF	14	127.5	5.9	486.8	124.0	28.2	29.0	22.7	3.5	2.7
Tolhwd	75	189.0	49.7	444.5	199.6	7.1	55.4	29.3	-10.6	-5.6

GMV NL		Observed			Prediction					
$m^3 ha^{-1}$	N	Mean	Min	Max	Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	137.7	97.1	192.3	156.3	11.1	27.4	19.9	-18.5	-13.4
HE	10	263.2	26.3	392.7	242.8	38.0	78.8	29.9	20.4	7.8
Intol	2	144.5	96.5	192.4	196.7	54.2	52.6	36.4	-52.2	-36.1
Low	6	102.1	36.5	209.9	104.8	29.2	36.8	36.0	-2.7	-2.6
MW	8	157.7	23.4	337.0	133.3	20.0	65.7	41.7	24.4	15.5
OAK	2	222.3	137.6	306.9	179.0	68.5	46.2	20.8	43.3	19.5
Pine	46	247.0	14.2	994.5	231.7	22.9	97.2	39.4	15.4	6.2
PJ	2	44.9	33.1	56.7	52.4	8.1	8.3	18.5	-7.5	-16.7
PR	15	348.8	105.8	811.5	283.5	40.1	118.4	33.9	65.3	18.7
SF	14	101.7	5.0	458.6	93.8	25.0	33.1	32.5	7.9	7.8
Tolhwd	75	139.4	14.3	394.7	152.6	7.2	52.4	37.6	-13.2	-9.5

GMV WL $m^3 ha^{-1}$	N	Observed Mean	Observed Min	Observed Max	Prediction Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	125.7	87.0	186.0	142.5	11.4	28.6	22.8	-16.8	-13.4
HE	10	253.0	20.8	383.2	229.8	37.5	77.7	30.7	23.1	9.1
Intol	2	134.2	86.4	181.9	177.6	59.4	44.9	33.5	-43.4	-32.3
Low	6	95.4	33.8	199.7	98.2	29.4	34.7	36.4	-2.8	-2.9
MW	8	147.8	18.9	320.0	123.7	19.4	64.2	43.4	24.0	16.2
OAK	2	210.2	123.4	297.0	171.4	68.0	43.1	20.5	38.8	18.5
Pine	46	241.6	13.4	987.5	225.2	22.5	96.7	40.0	16.4	6.8
PJ	2	40.0	28.5	51.4	47.8	9.1	8.2	20.5	-7.8	-19.5
PR	15	339.4	105.4	798.7	274.1	38.8	119.1	35.1	65.3	19.2
SF	14	95.7	4.6	451.5	87.9	24.3	33.5	35.0	7.8	8.2
Tolhwd	75	130.3	7.8	387.2	143.9	7.2	51.3	39.4	-13.7	-10.5

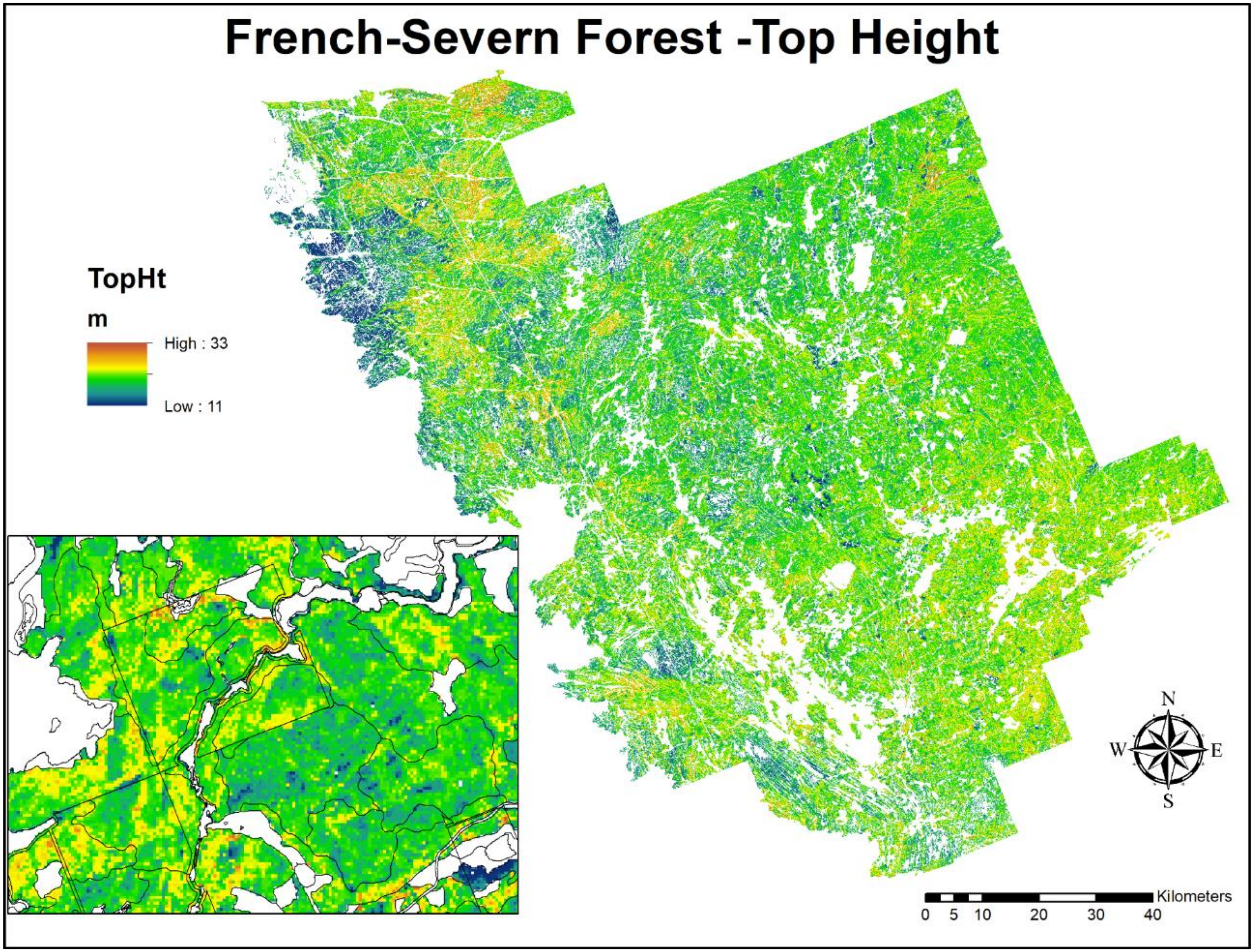
Biomass $T ha^{-1}$	N	Observed Mean	Observed Min	Observed Max	Prediction Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	171.7	104.9	195.0	190.6	10.1	26.3	15.3	-18.9	-11.0
HE	10	230.2	49.2	293.6	190.9	19.3	57.6	25.0	39.3	17.1
Intol	2	160.4	113.4	207.4	175.4	26.0	25.8	16.1	-15.0	-9.4
Low	8	59.1	4.1	172.5	75.5	24.0	30.0	50.8	-16.4	-27.7
MW	8	139.4	35.3	312.2	129.0	19.4	39.3	28.2	10.5	7.5
OAK	2	242.1	148.5	335.7	193.5	43.5	69.8	28.8	48.6	20.1
Pine	46	144.7	8.4	552.4	140.6	13.0	48.2	33.3	4.1	2.8
PJ	2	38.8	31.9	45.7	49.7	0.1	12.9	33.2	-10.9	-28.1
PR	15	181.1	57.7	409.6	151.9	18.0	56.9	31.4	29.3	16.2
SF	14	74.6	3.0	255.0	73.1	14.8	21.0	28.2	1.5	2.0
Tolhwd	75	162.0	47.3	385.2	173.0	6.1	44.4	27.4	-11.0	-6.8

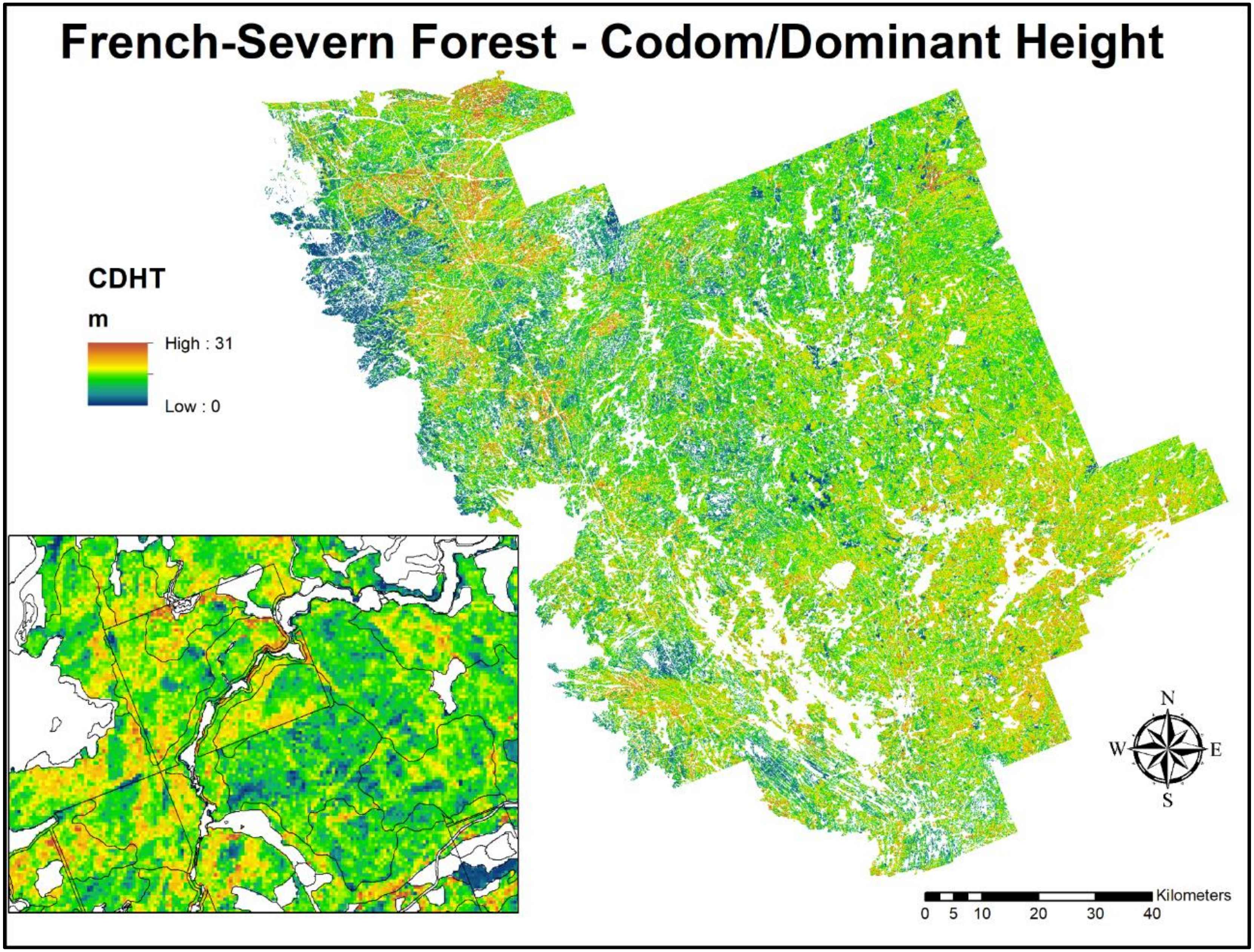
Density Stems ha^{-1}	N	Observed Mean	Observed Min	Observed Max	Prediction Mean	StdErr	RMSE	RMSE%	BIAS	BIAS%
BY	8	641	350	975	710	66.9	250	39.0	-69	-10.8
HE	10	618	300	1200	680	109.3	161	26.1	-62	-10.1
Intol	2	1263	550	1975	909	174.5	644	51.0	354	28.0
Low	8	694	125	2100	642	175.0	262	37.7	52	7.5
MW	8	1016	650	1650	853	99.0	325	32.0	162	16.0
OAK	2	688	575	800	512	50.6	240	34.8	175	25.5
Pine	46	566	25	1475	556	42.0	210	37.0	9	1.7
PJ	2	775	725	825	641	101.9	144	18.6	134	17.3
PR	15	640	25	1275	523	78.2	240	37.4	117	18.3
SF	14	1077	25	2050	783	109.9	471	43.7	294	27.3
Tolhwd	75	636	150	1700	621	25.3	193	30.4	15	2.4

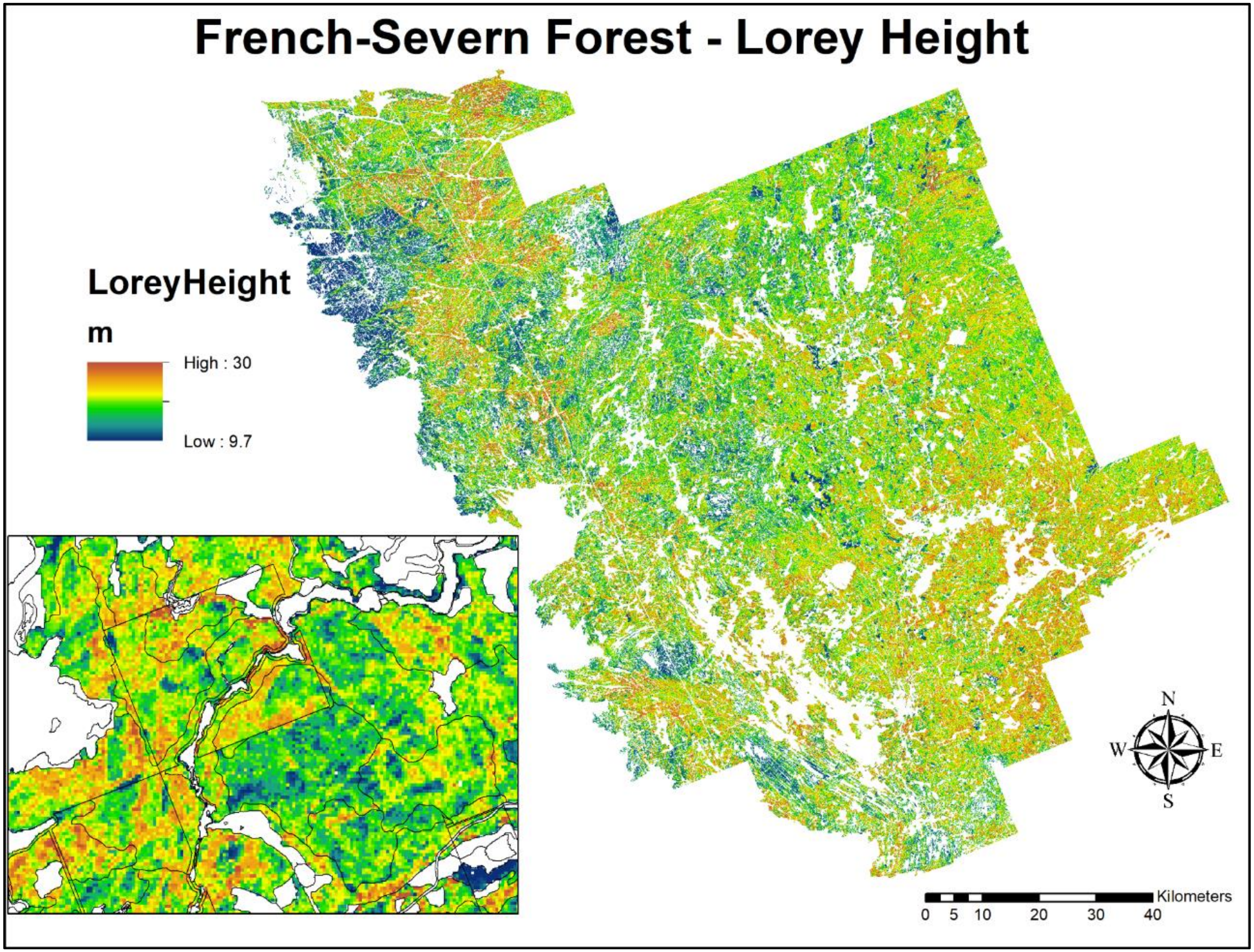


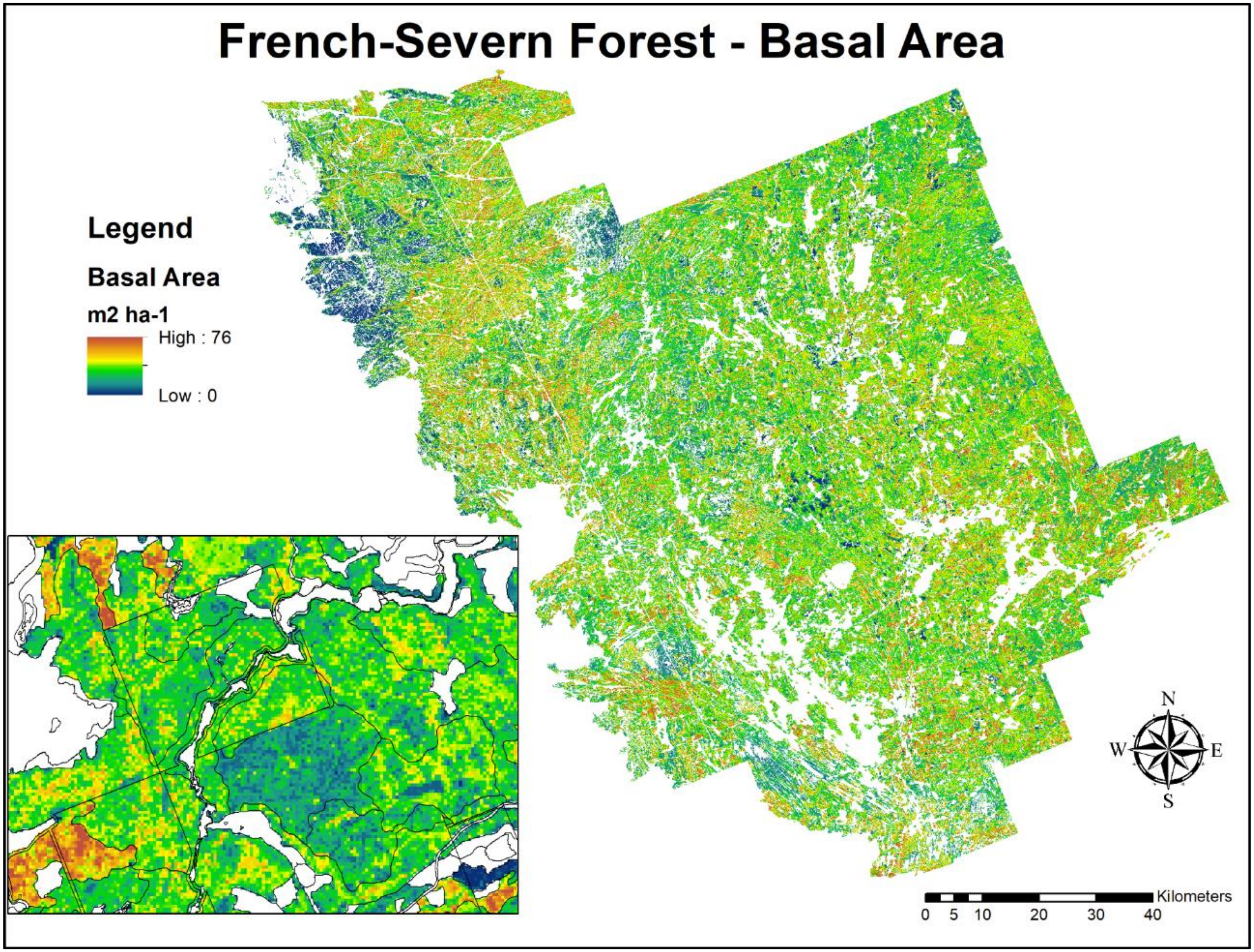
10-Fold cross validation RMSE (%) results of plot level predictions by AFA Forest Unit. Included are the number of calibration plots (in brackets) and % of forested landscape area the FU occupies.

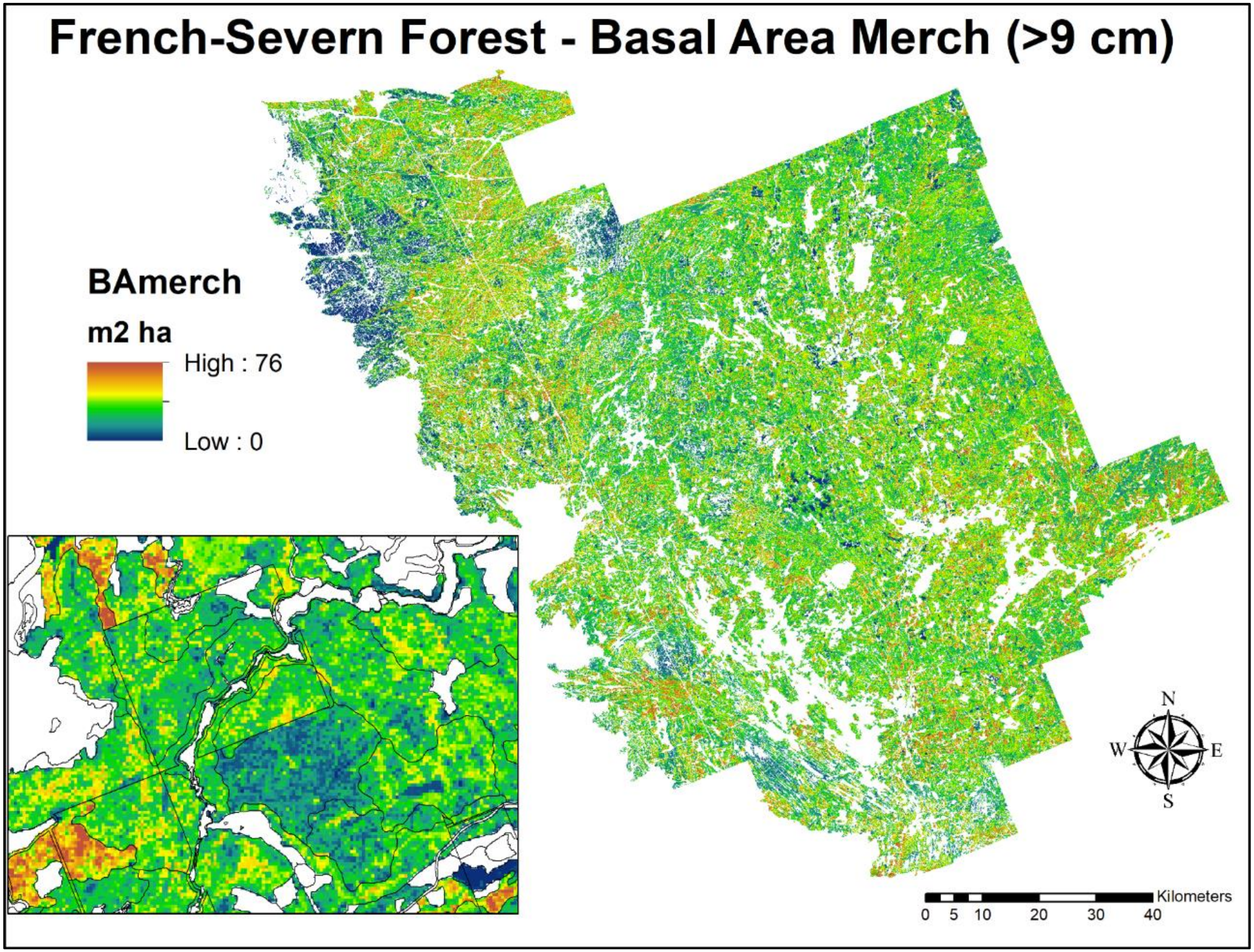
Appendix C – FSF Inventory Rasters

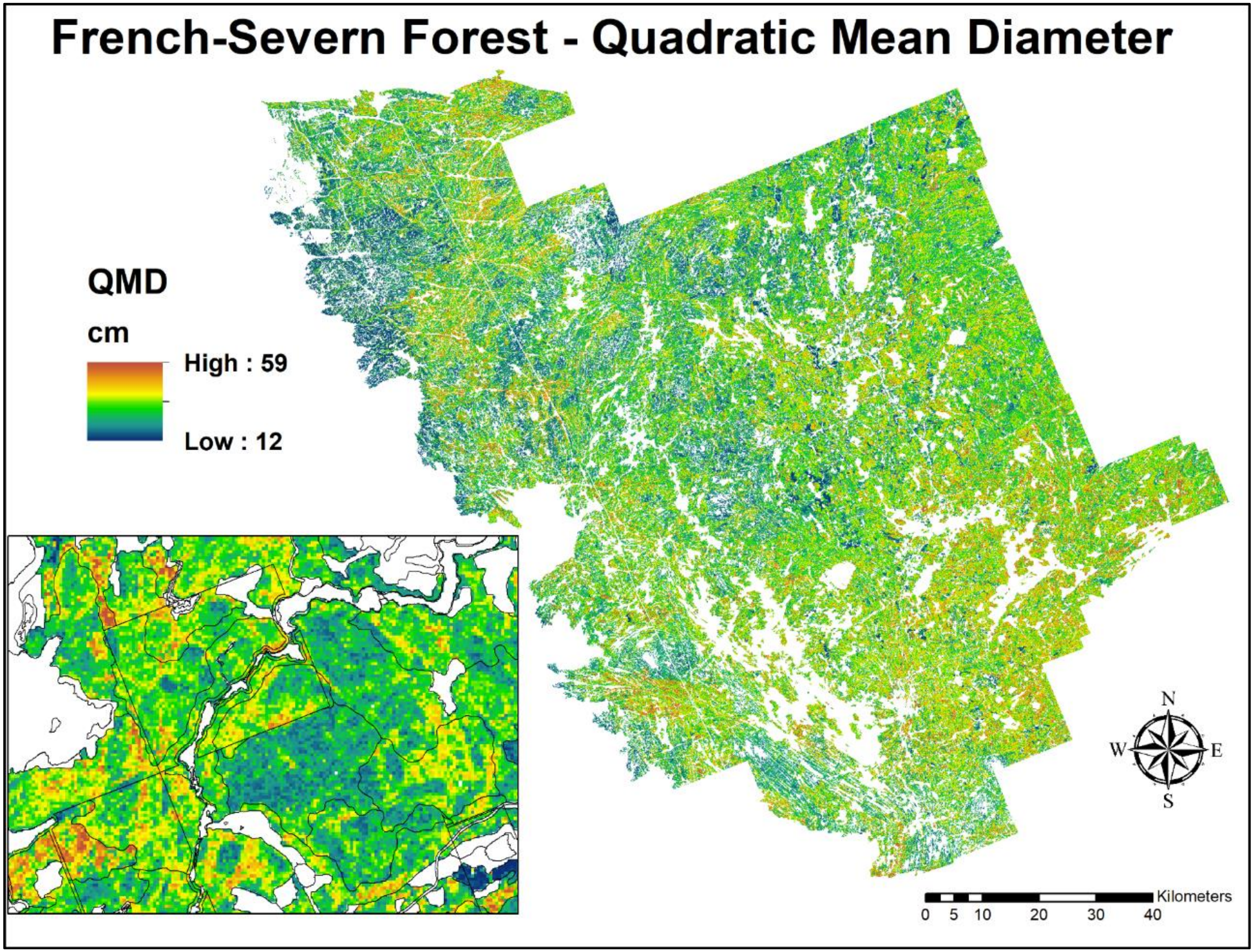

French-Severn Forest -Top Height
TopHt
m
High : 33
Low : 11
N
W
E
S
Kilometers
0 5 10 20 30 40

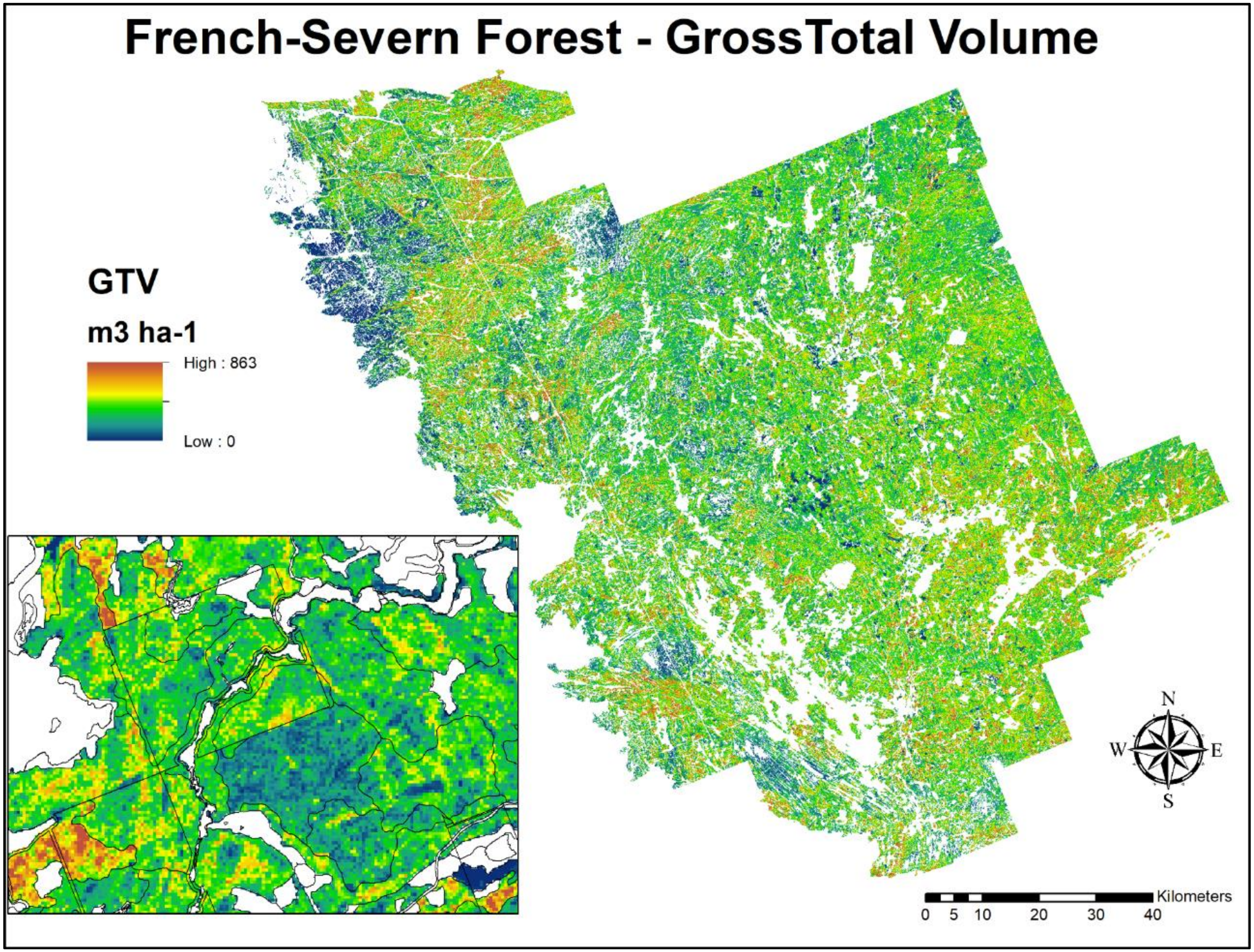

French-Severn Forest - Codom/Dominant Height
CDHT
m
High : 31
Low : 0
N
W
E
S
Kilometers
0 5 10 20 30 40

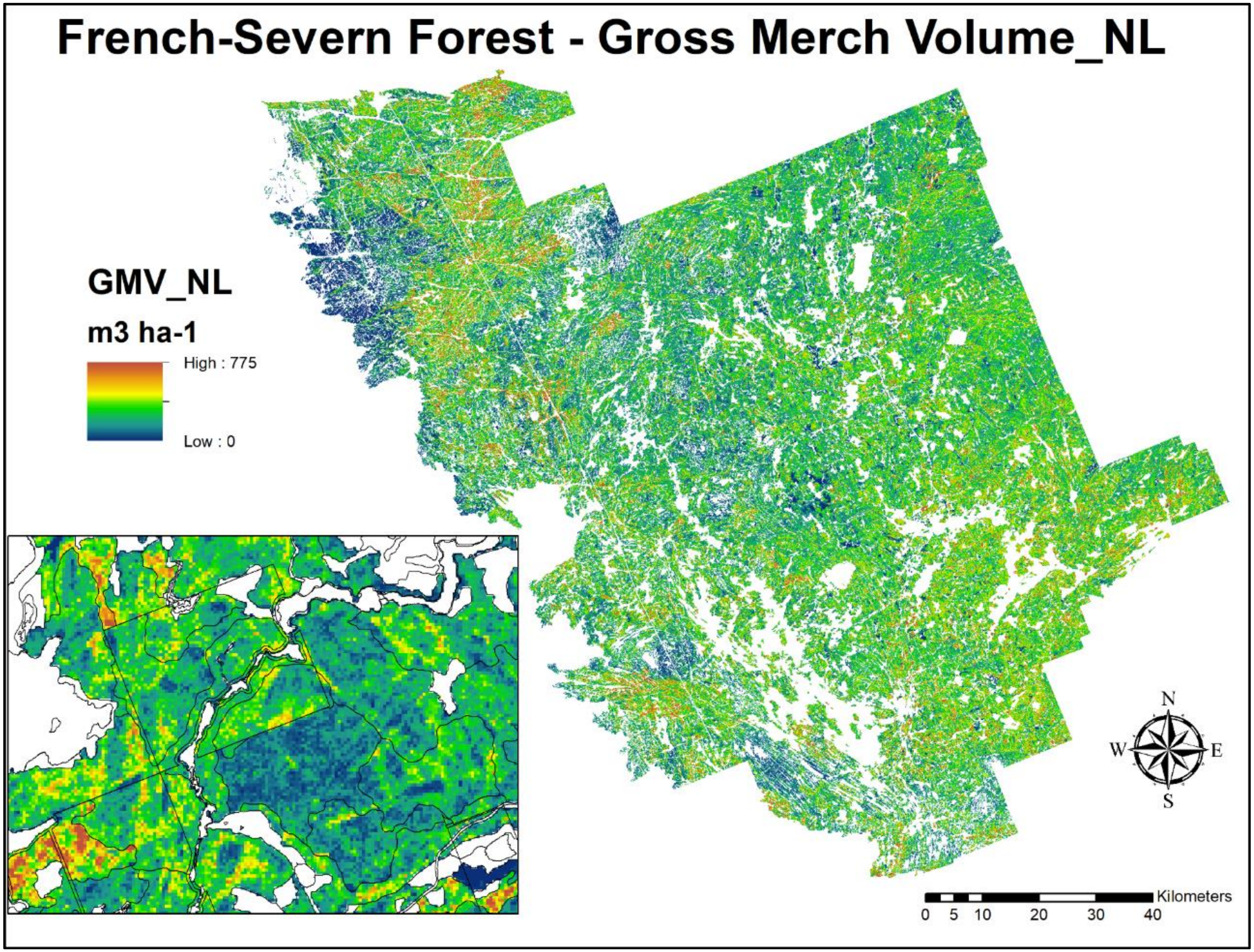

French-Severn Forest - Lorey Height
LoreyHeight
m
High : 30
Low : 9.7
N
W
E
S
Kilometers
0 5 10 20 30 40

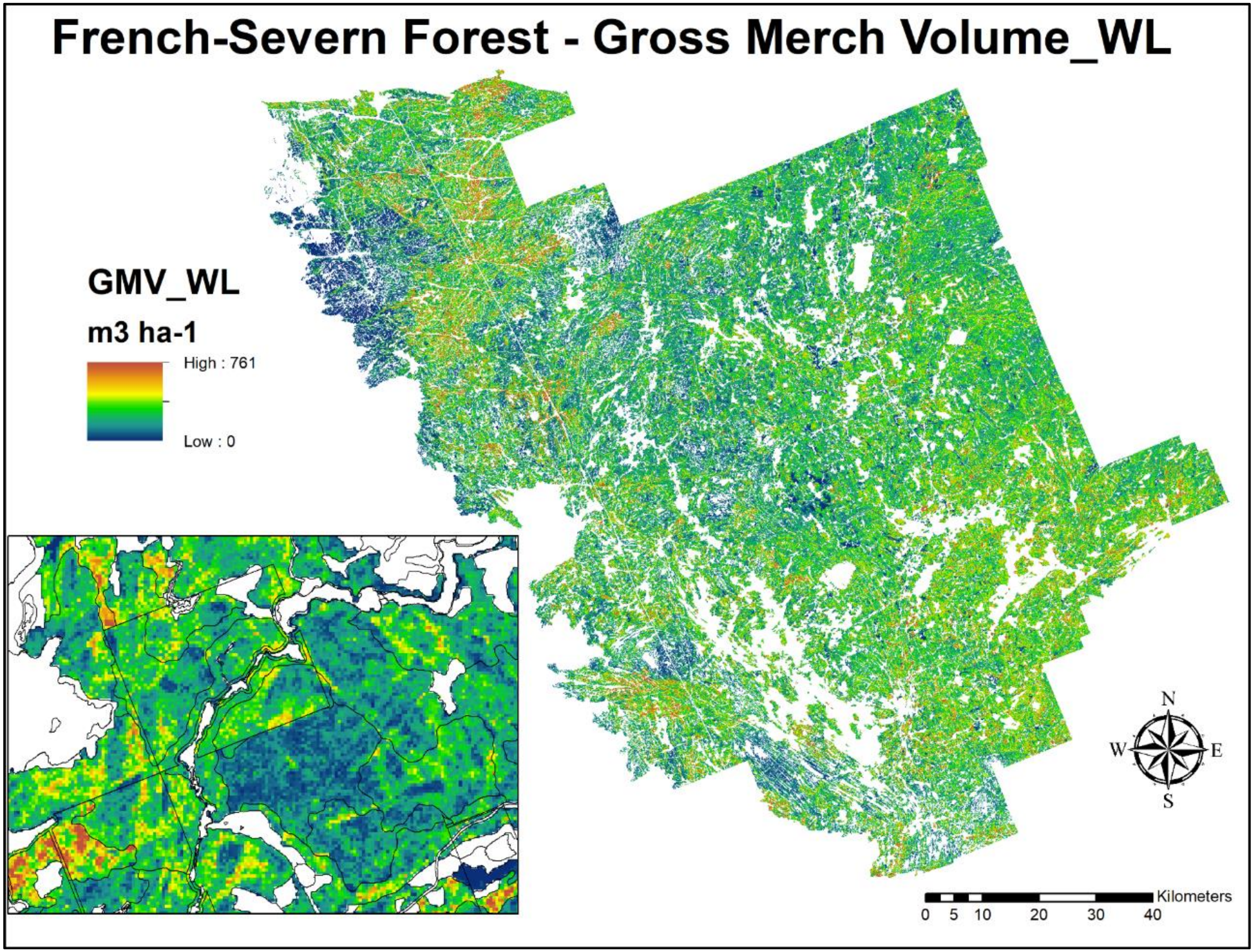

French-Severn Forest - Basal Area
Legend
Basal Area
m2 ha-1
High : 76
Low : 0
N
W
E
S
Kilometers
0 5 10 20 30 40

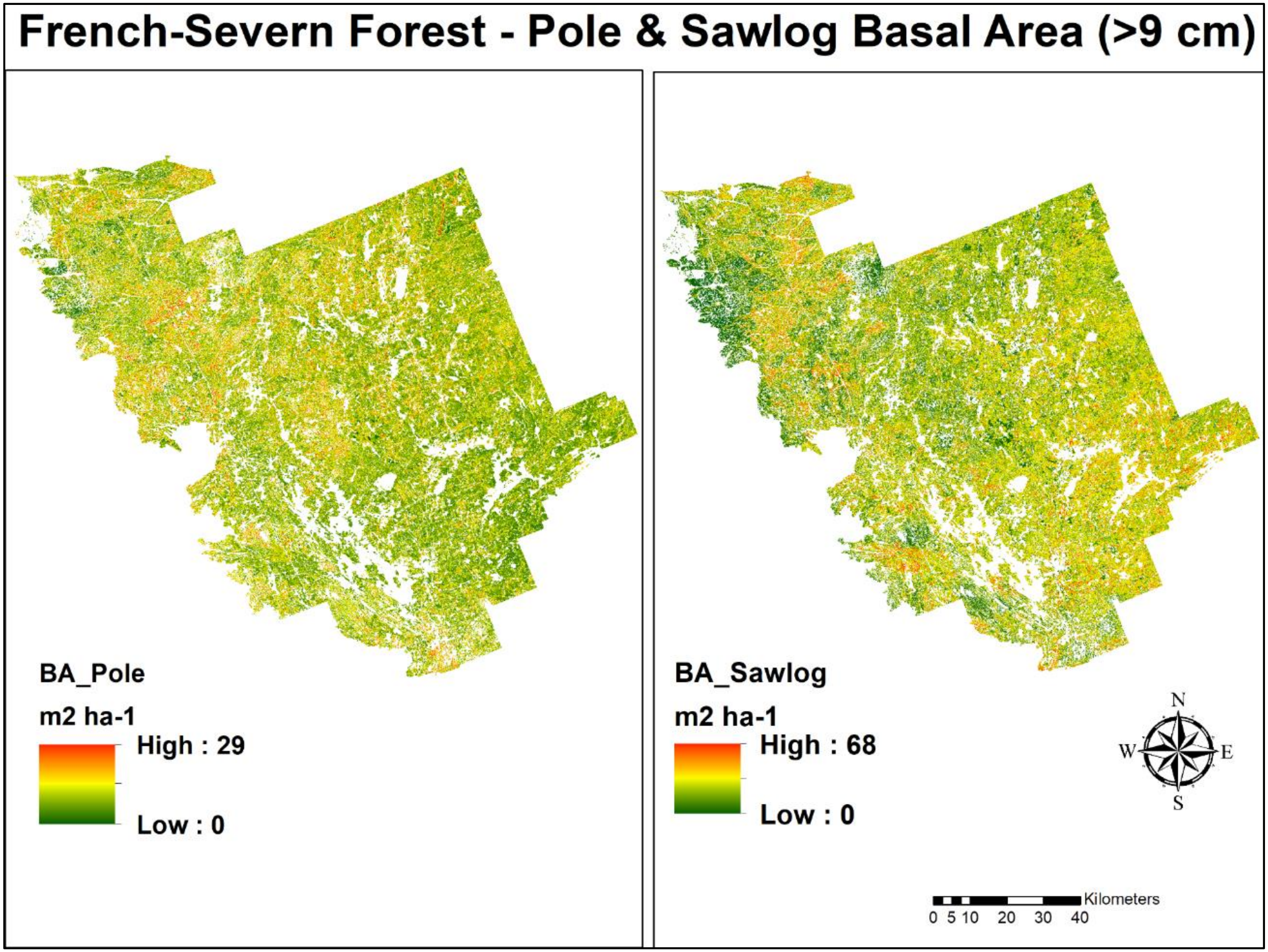

French-Severn Forest - Basal Area Merch (>9 cm)
BAmerch
m2 ha
High : 76
Low : 0
N
W
E
S
Kilometers
0 5 10 20 30 40

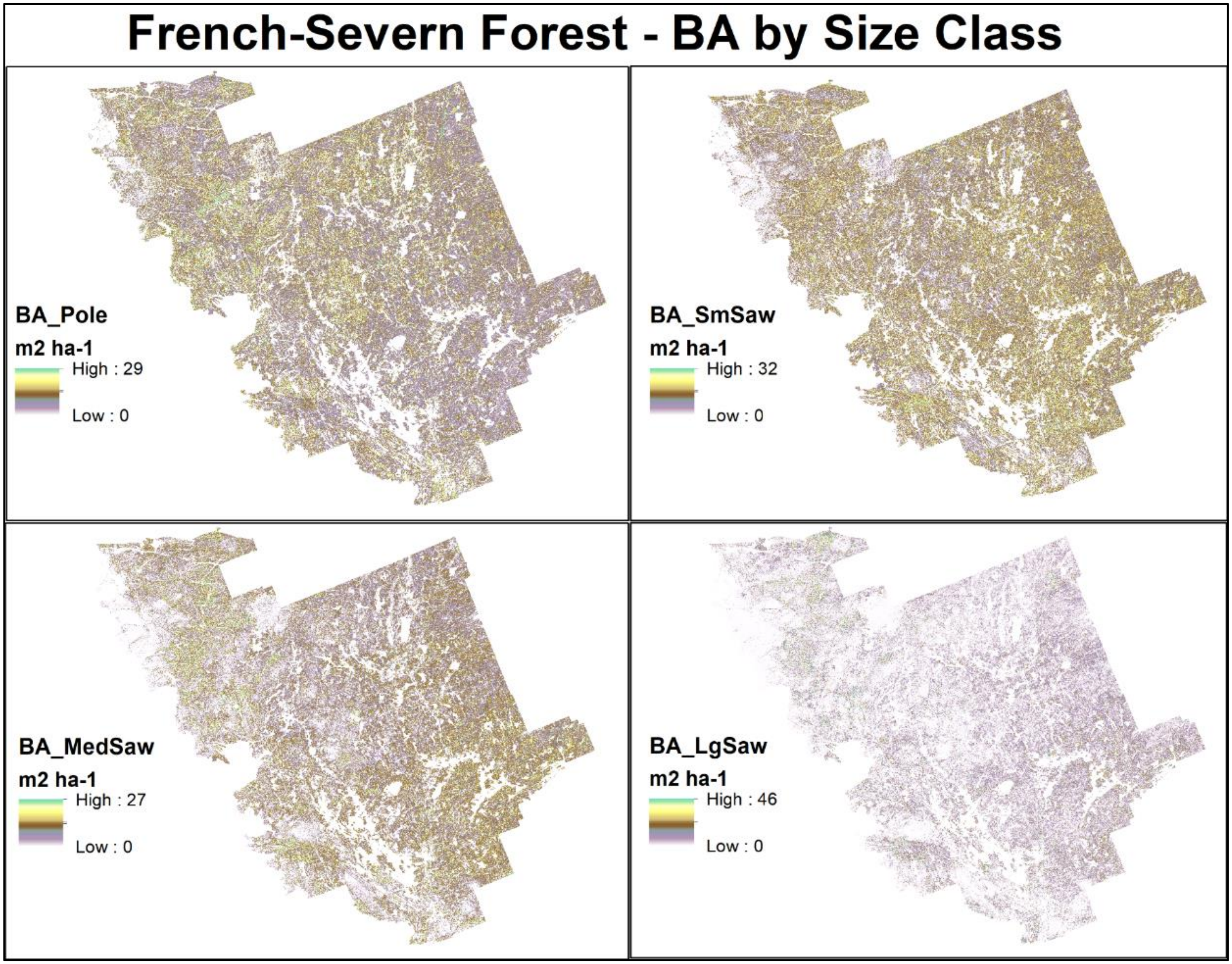

French-Severn Forest - Quadratic Mean Diameter
QMD
cm
High : 59
Low : 12
N
W
E
S
Kilometers
0 5 10 20 30 40

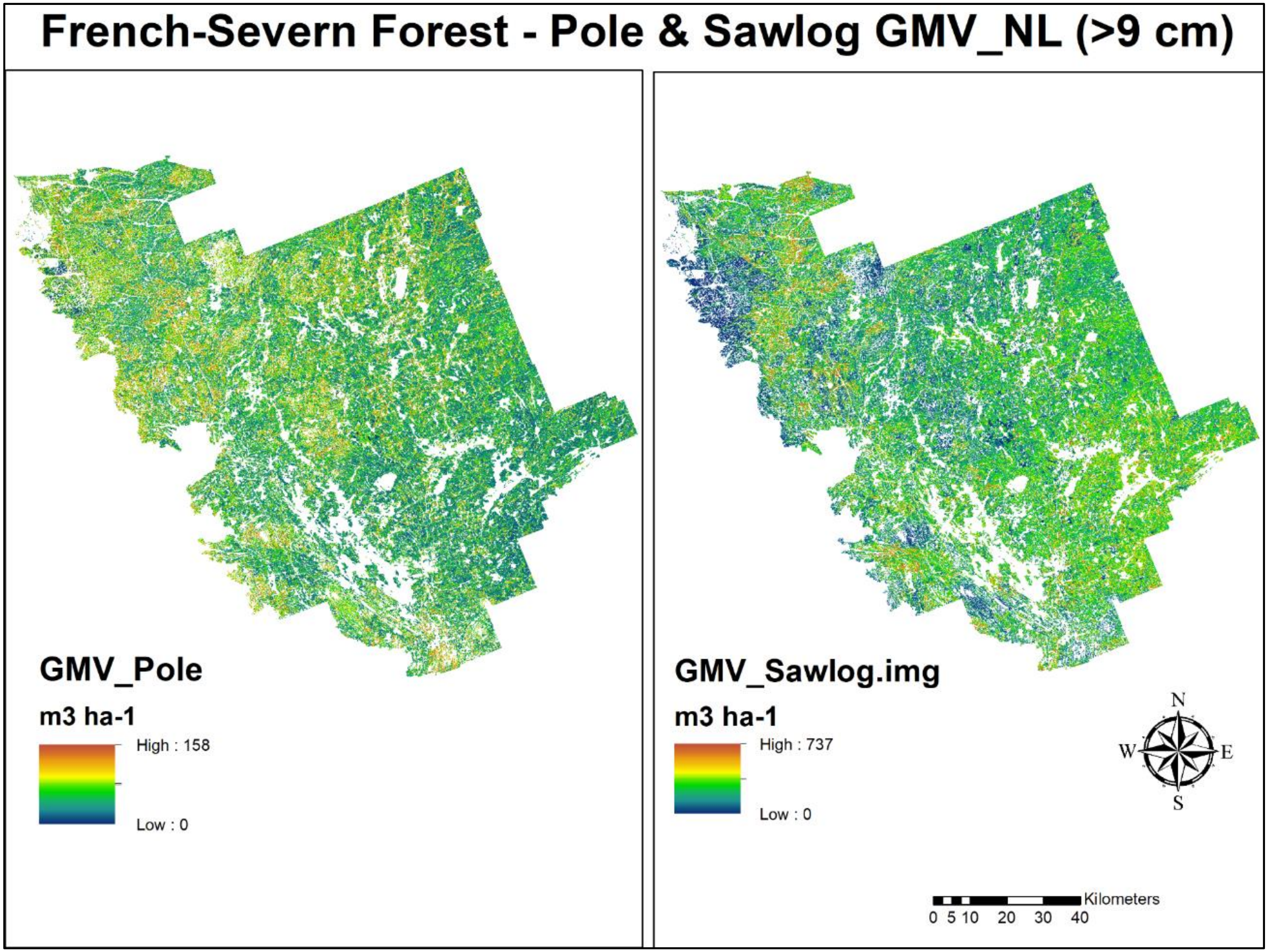

French-Severn Forest - GrossTotal Volume
GTV
m3 ha-1
High : 863
Low : 0
N
W
E
S
Kilometers
0 5 10 20 30 40

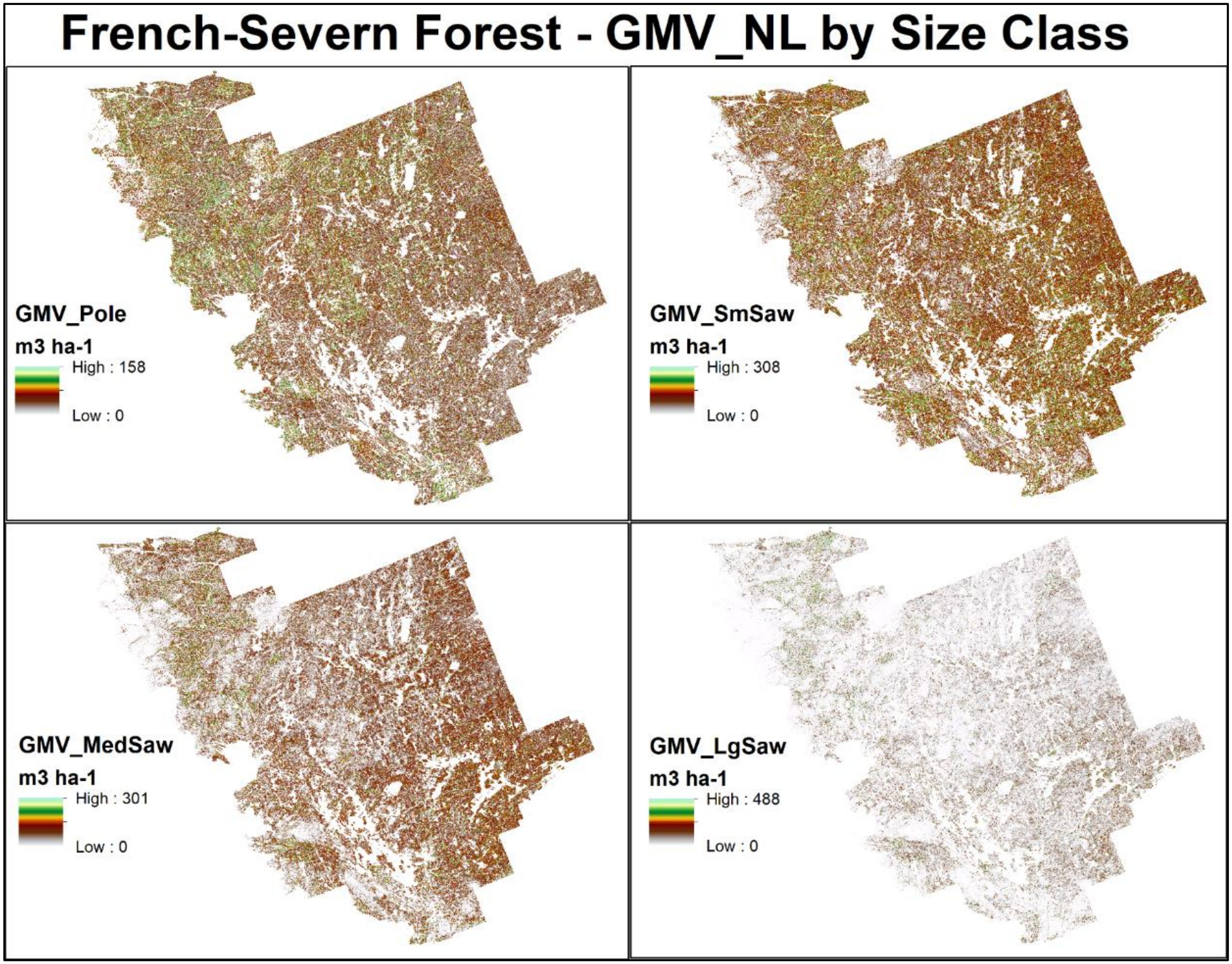

French-Severn Forest - Gross Merch Volume_NL
GMV_NL
m3 ha-1
High : 775
Low : 0
N
W
E
S
Kilometers
0 5 10 20 30 40

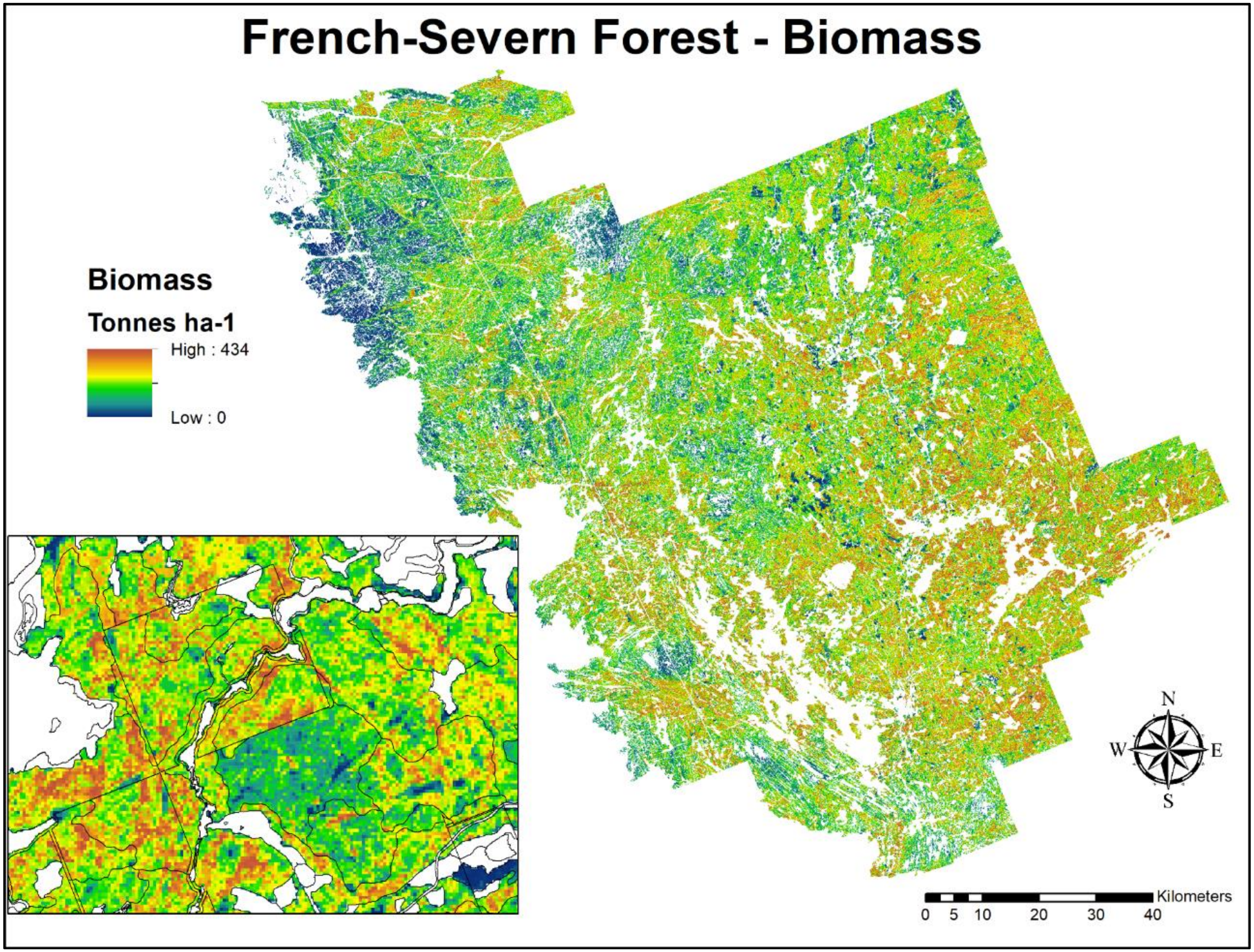

French-Severn Forest - Gross Merch Volume_WL
GMV_WL
m3 ha-1
High : 761
Low : 0
N
W
E
S
Kilometers
0 5 10 20 30 40

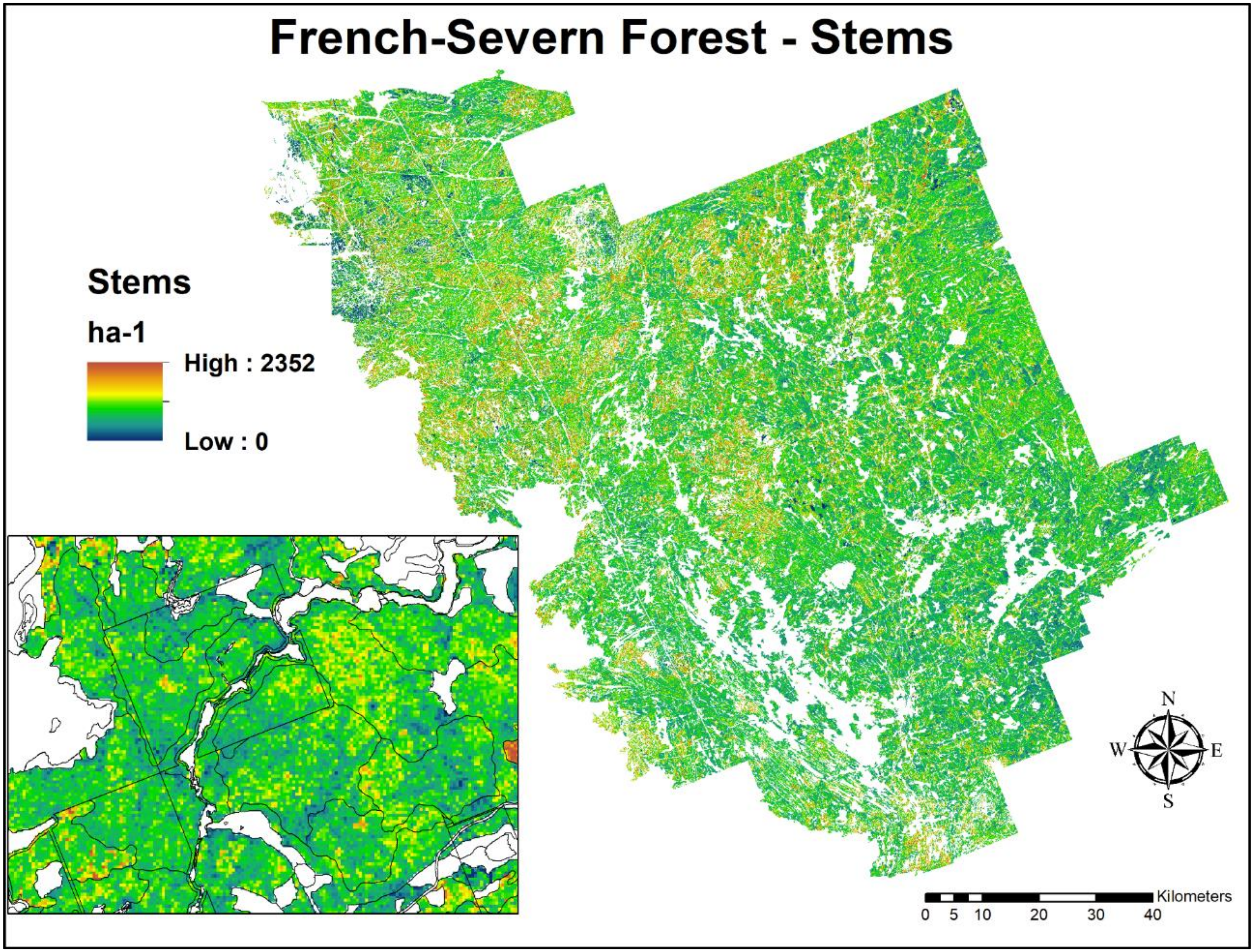

French-Severn Forest - Pole & Sawlog Basal Area (>9 cm)
BA_Pole
m2 ha-1
High : 29
Low : 0
BA_Sawlog
m2 ha-1
High : 68
Low : 0
N
W
E
S
Kilometers
0 5 10 20 30 40


French-Severn Forest - BA by Size Class
BA_Pole
m2 ha-1
High : 29
Low : 0
BA_SmSaw
m2 ha-1
High : 32
Low : 0
BA_MedSaw
m2 ha-1
High : 27
Low : 0
BA_LgSaw
m2 ha-1
High : 46
Low : 0


French-Severn Forest - Pole & Sawlog GMV_NL (>9 cm)
GMV_Pole
m3 ha-1
High : 158
Low : 0
GMV_Sawlog.img
m3 ha-1
High : 737
Low : 0
N
W
E
S
Kilometers
0 5 10 20 30 40


French-Severn Forest - GMV_NL by Size Class
GMV_Pole
m3 ha-1
High : 158
Low : 0
GMV_SmSaw
m3 ha-1
High : 308
Low : 0
GMV_MedSaw
m3 ha-1
High : 301
Low : 0
GMV_LgSaw
m3 ha-1
High : 488
Low : 0


French-Severn Forest - Biomass
Biomass
Tonnes ha-1
High : 434
Low : 0
N
W
E
S
Kilometers
0 5 10 20 30 40


French-Severn Forest - Stems
Stems
ha-1
High : 2352
Low : 0
N
W
E
S
Kilometers
0 5 10 20 30 40

Appendix D – Site Index Curve Sources

Sharma and Reid (2018) recommend that height and age be estimated from at least five independent sample within a stand and for trees that have at least 6 years of growth beyond breast height age.

Table 1. The available site index curves are listed by species and origin.

Species	Planted	Natural
White pine	Sharma & Parton (2019) equation 1, table 2 no climate	Parresol & Vissage (1998)
Red pine	Sharma & Parton (2018b) equation 1, table 4 (no climate)	Buckmann et al. (2006)
Jack pine	Sharma et al. (2015) equation 1 (no climate)	Sharma & Reid (2018), equation 3, table 4
White spruce	Sharma & Parton (2018a) equation 1, table 2 (no climate)	
Black spruce	Sharma et al. (2015) equation 1 (no climate)	Sharma & Reid (2018), equation 3, table 4
Hemlock		Carmean et al. (1989) figure 127
Balsam fir		Carmean (1996) figure 18
Tamarack		Carmean (1996) figure 16
cedar		Carmean et al. (1989) figure 57
Sugar maple		Buda & Wang (2006)
Red maple		Carmean et al. (1989) figure 1
Yellow birch		Carmean et al. (1989) figure 6
White birch		Carmean (1996) figure 14
Poplar (all including Aspen, largetooth and balsam poplar)		Carmean et al. (2006)
White ash		Carmean et al. (1989) figure 13
Black ash		Carmean et al. (1989) figure 14
Red oak		Carmean et al. (1989) figure 48
Elm		Carmean et al. (1989) figure 53
Basswood		Carmean et al. (1989) figure 51
Beech		Carmean et al. (1989) figure 11
Black cherry		Carmean et al. (1989) figure 34

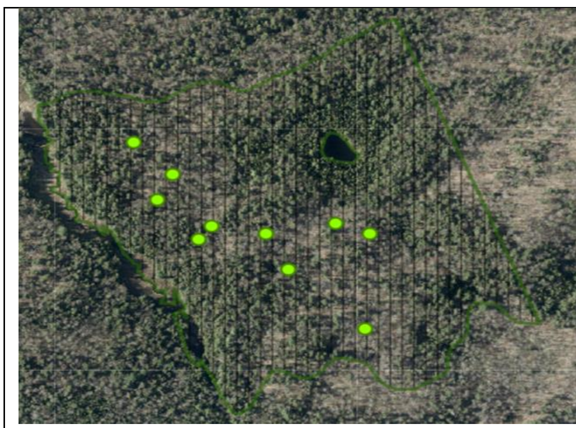
Appendix E – Implemented FSF Forest Unit SQL

Order	FU	FSF SQL Query
1	**PR**	([PR]>=70) AND ([PW]<30)
2	**PWUS4**	([PW]+[PR]>=50) AND ([PW]>[PR]) AND (([PW]+[PR])*[STKG] >=30) AND ([OR]+[OB]+[OW]<20)
3	**PWOR**	([PW]+[PR]+[OR]+[OW]+[Ob]>=50) AND ([PW]>=[OR]+[OB]+[OW]) AND (([PW]+[PR]+[OR]+[OB]+[OW])*[STKG] >=30) AND ([OR]+[OB]+[OW]>=20)
4	**PWUSC**	((PW+PR>=30) AND ((PW+PR)*[STKG] >=30)) OR ((PW>=HE) AND (PW>=SW) AND (PW>(CE +CW)) AND (PW>=[Or]) AND ((PW+PR) >=30) AND ((PW+PR+SW+HE+[Or]+PJ+CE+CW)*[STKG] >=30) AND ((PW+PR+PJ+SW+SB+SR+SX+HE+BF+CE+CW+LA)>=80))
5	**PWUSH**	((PW>=PR) AND ((PW+PR)>=30) AND ((PW+PR)*[STKG] >=30)) OR ((PW>=PR) AND (PW>=HE) AND (PW>=SW) AND (PW>(CE+CW)) AND (PW>=[OR]) AND (PW+PR>=30) AND ((PW+PR+SW+HE+[Or]+ PJ+CE+CW)*[STKG] >=30) AND (PW+PR+PJ+SW+SR+SX+SB+HE+BF+CE+CW+LA <80))
6	**PWST**	([PW]+[PR]>=30) AND ([PW]+[PR]>=[HE]) AND ([PW]+[PR]>=[SW]) AND ([PW]+[PR]>=[SB]+[SR]+[SX]) AND ([PW]+[PR]>=([CE]+[CW])) AND ([PW]+[PR]>=[OR])
7	**PJ1**	([PJ]>=70) AND ([MH]+[AB]+[AW]+[BD]+[BE]+[CH]+[EW]+[IW]+[OR]+[BY]+[OW]+[Ob]+[PO] +[Pt]+[Pb]+[Pl]+[BW]+[MR]+[MS]+[AX]+[CB]+[EX]+[HI]+[BN]<=20)
8	**PJ2**	((([PJ]+[SB]+[SR]+[SX]+[PR]>=70) OR (([PJ]>=50) AND ([PJ]+[SB]+[SR]+[SX]+[BF]+[SW]+[HE]+[PW]+[PR]+[CE]+[CW]+[LA]>=70) AND ([BF]+[SW]+[HE]+[PW]+[CE]+[CW]+[LA]<=20))) AND ([PJ]>=[SB]+[SR]+[SX]))
9	**HE**	([HE]>=40)
10	**CE**	([CE]+[CW]>=40) AND (([CE]+[CW])>=[SB]+[SR]+[SX]+[LA]+[BF]) AND ([OW]+[Ob]+[EW]+[IW]+[CH]+ [MH]+[AB]+[AW]+[BD]+[BE]+[OR]+[BY]+[PO]+[Pt]+[Pl]+[BW]+[MR]+[MS]+[EX]+[CB]+[AX]+[HI]+[BN]<30)
11	**SB**	([SB]+[SR]+[SX]>=80) AND ([MH]+[AW]+[BD]+[BE]+[CH]+[IW]+[OR]+[OW]+[Ob]+[BY]+[PR]+[BN]+ [HI]+[CB]=0) AND ([PW]+[PJ]<=10)
12	**LC**	([SB]+[SX]+[SR]+[CE]+[CW]+[LA]>=80) AND ([MH]+[AW]+[BD]+[BE]+[CH]+[IW]+[OR]+[OW]+[Ob]+[BY]+[PR]+[CB]+[HI]+[BN]=0) AND ([PW]+[PJ]<=10)
13	**SP1**	([SB]+[SW]+[SR]+[SX]+[BF]+[CE]+[CW]+[LA]+[PW]+[PJ]+[PR]+[HE]>=70) AND (([BF]+[CE]+[CW]+[PW]+[LA]+[SW]+[HE]<=20) OR ([PJ]>=30))
14	**SF**	([SW]+[SR]+[SB]+[SX]+[PW]+[PR]+[PJ]+[BF]+[CE]+[CW]+[LA]+[HE]>=70)
15	**BY**	([BY]>=40)
16	**OAK**	([OR]>=[MH]+[BE]) AND ([OR]>=30) AND ([OR]+[MH]+[AW]+[AB]+[BE]+[BD]+[BY]+[PW]+[PR]+[SW]+[HE]+[AX]>=40)
17	**HDSL2**	(([BD]+[AW]+[CH]+[OR]+[OW]+[Ob]+[CB]>=30) OR (([BE]+[OR]+[OW]+[Ob]>=30) OR ([BE]>=20)))
18	**HDSL1**	([MH]+[AW]+[BD]+[BE]+[CH]+[EW]+[IW]+[OR]+[BY]+[OW]+[Ob]+[HE]+[EX]+[CB]>=50) AND ([PO]+[Pt]+[Pb]+[Pl]+[BW]+[BF]<=30) AND ([SC] <= 2)
19	**LWMW**	([CE]+[CW]+[AB]+[LA]+[SB]+[AX]+[SR]+[SX]>=30) AND (([AB]+[AX]>=20) OR ([AB]+[AX]+[MR]+[MS]+[BY]>=30))
20	**HDUS**	([MH]+[AW]+[BD]+[BE]+[CH]+[EW]+[IW]+[OR]+[BY]+[OW]+[Ob]+[HE]+[CB]+[HI]+[EX]+[BN]>=50)
21	**PO**	([PO]+[Pt]+[Pb]+[Pl]>=50) AND ([MH]+[AB]+[AW]+[BD]+[BE]+[CH]+[EW]+[IW]+[OR]+[BY]+[OW]+[Ob]+[PO]+[Pb]+[Pt]+[Pl]+[BW]+[MR]+[MS]+[AX]+[BN]+[CB]+[EX]+[HI]>=70)
22	**BW**	([PO]+[Pt]+[Pb]+[Pl]+[BW]>=50) AND ([MH]+[AB]+[AW]+[BD]+[BE]+[CH]+[EW]+[IW]+[OR]+[BY]+[OW]+[Ob] +[PO]+[Pt]+[Pb]+[Pl]+[BW]+[MR]+[MS]+[AX]+[BN]+[CB]+[EX]+[HI]>=70)
23	**MWUS**	(([SW]+[PW]+[PR]+[CE]+[CW]+[MH]+[BY]+[AW]+[CH]+[BD]+[OR]+[OW]+[Ob]+[IW]+[BE]+[HE]+[CB]+[HI]+[BN])*[STKG] >=30)
24	**MWD**	([PJ]+[PW]+[PR]>=20)
25	**MWR**	Default

Appendix F – Excluded OPC Cruised Stands from Validation

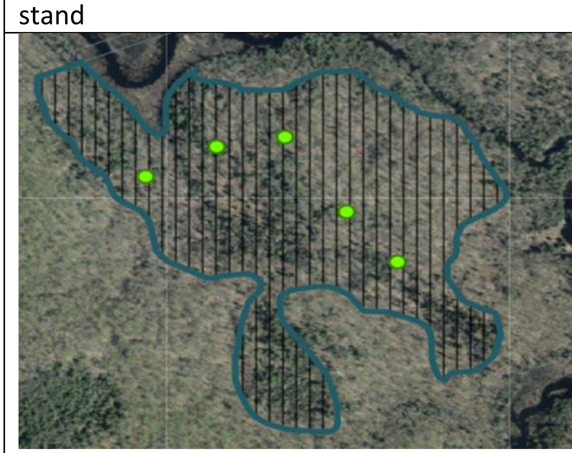
The following list of OPC cruised stands were excluded from the stand level validation exercise. The primary reasons for their exclusion were their lack of sampling for the full range of species (i.e. conifer portions) within the stands. Some examples are provided below.

							LiDAR Weighted Zonal Stats		
Stand	Forest Type	Plots	Area ha	Bamerch (m^2 ha^{-1})	BA Poles (m^2 ha^{-1})	BA Sawlogs (m^2 ha^{-1})	BAmerch (m^2 ha^{-1})	BA Poles (m^2 ha^{-1})	BA Sawlogs (m^2 ha^{-1})
LIV169232	Hwd_Sel	9	28.2	21.3	4.4	16.9	34.0	12.0	21.9
LIV170723	Hwd_Sel	3	6.8	18.7	2.0	16.7	24.6	7.1	17.5
BLR10643	Pine_US	5	9.9	20.4	9.2	11.2	31.0	12.0	19.0
BET118815	Hwd_Sel	8	21.3	20.8	7.5	13.3	25.8	9.5	16.3
BET92069	Hwd_Sel	5	48.7	18.8	8.0	10.8	26.4	8.5	17.9
MCR92326	Hwd_Sel	3	18.7	20.0	8.7	11.3	27.2	9.9	17.2
MLN229837	Hwd_Sel	3	17.2	33.8	10.9	22.9	20.6	6.4	14.2
		Mean		**22.0**	**7.2**	**14.7**	**27.1**	**9.4**	**17.7**

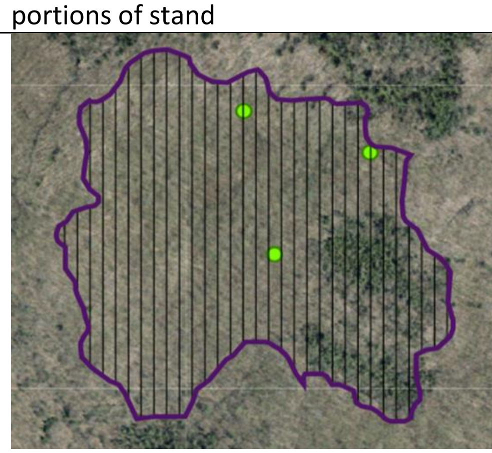


LIV169232 – Did not sample hemlock portions of stand

LIV170723 – Did not sample conifer portions of stand



MLN229837 – Did not sample conifer portions of stand



MCR92326 - Did not sample conifer portions of stand