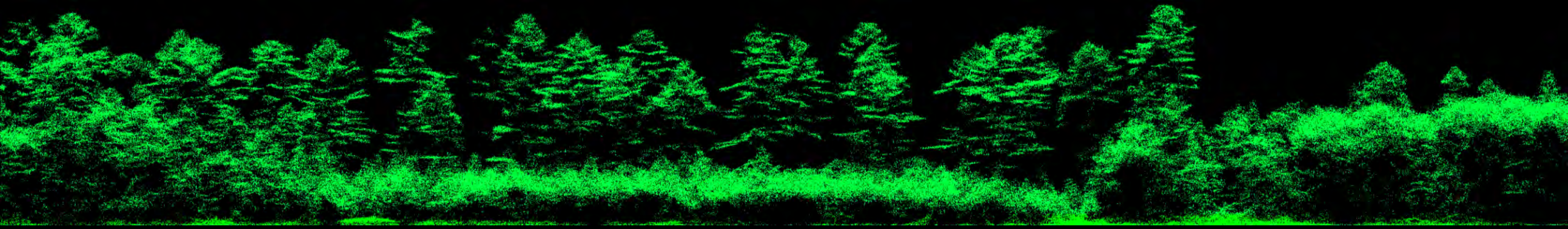
Exploring the innovation potential of single photon lidar for Ontario's eFRI

KTTD 5B-2018



February 18, 2021

Dr. Joanne White
Research Scientist
Canadian Forest Service

Murray Woods
Retired, OMNRF

Canada

Collaboration and partnerships

Co-leads:* *Joanne White (CFS), Murray Woods (OMNRF, CWFC), Jordan McMillan (CIF)

Funding:

Forestry Futures Trust; Canadian Institute of Forestry (CIF); Canadian Wood Fibre Centre, Canadian Forest Service

Canada Centre for Mapping and Earth Observation (CCMEO); Canadian Nuclear Laboratories (CNL)

OMNRF funded the RTK survey

FORESTRY FUTURES TRUST ONTARIO

Collaborators and contributors:

Dr. Margaret Penner, *Forest Analysis Ltd.;* Brian Batchelor, *Canadian Institute of Forestry;* Melissa Vekeman, Peter Arbour, and Kyle Harbin, *Canadian Wood Fibre Centre;* Annie Morin, *Canadian Nuclear Laboratories;* David Bélanger and Charles Papasodoro, *Canada Centre for Mapping and Earth Observation;* Thomas Krahn, Craig Onafrychuk ,and Ian Sinclair, *Ontario Ministry of Natural Resources and Forestry;* Dr. Jili Li, *FPInnovations;* Jean-Francois Prieur, *Université de Sherbrooke;* Field crews who collected valuable reference data for assessing terrain and forest characteristics; Regional forest managers for letters of support

Natural Resources Canada | Ressources naturelles Canada | Canadian Forest Service | Service canadien des forêts

Canadian Institute of Forestry | Institut Forestier du Canada

Ontario | Ministry of Natural Resources and Forestry

FPInnovations

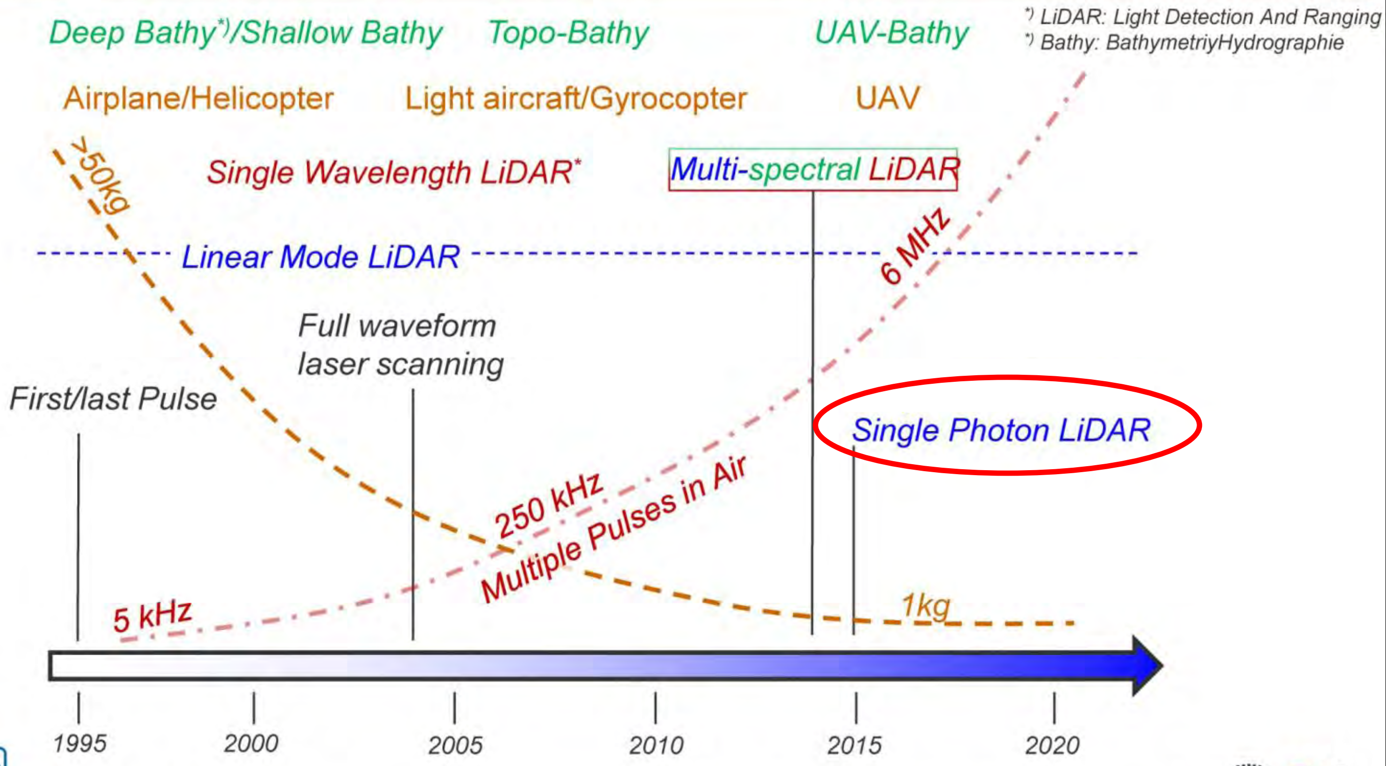
CIF-IFC SEEK | Science-Extension-Education-Knowledge | A NATIONAL TREE-ROOTS PARTNERSHIP

Project objectives

1. Quantify the performance of single photon lidar (SPL) in an area-based approach to estimating forest inventory attributes;

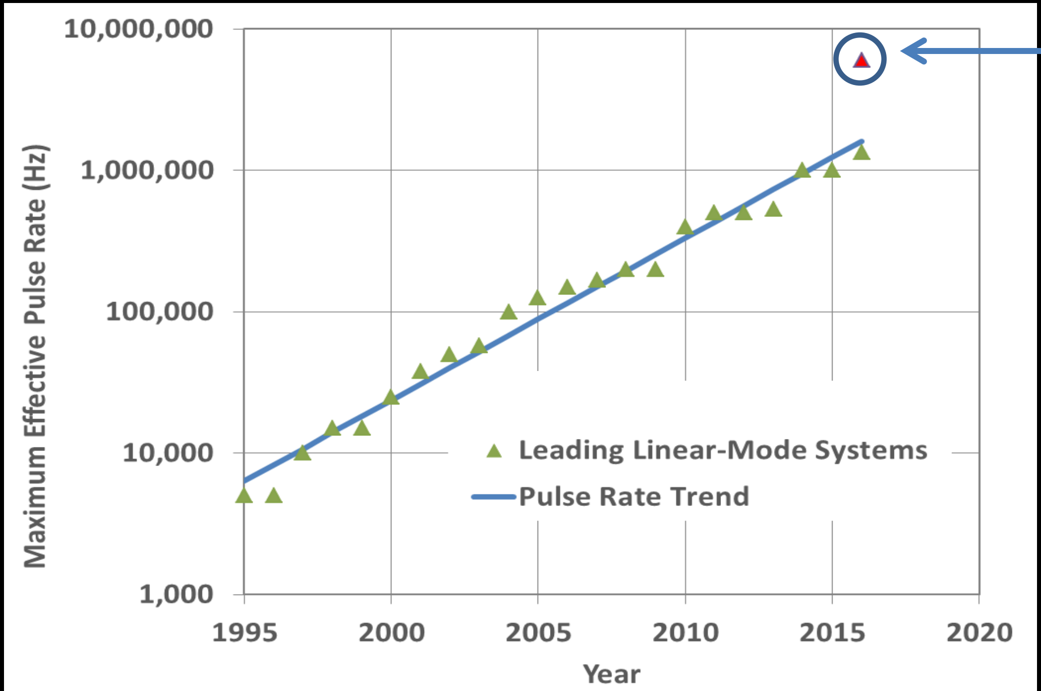
2. Quantify the performance of SPL for characterizing the terrain surface under varying forest types and canopy densities.

Timeline Airborne Laser Scanning



Source: G. Mandleburger

SPL starts at 6 million pulses per second



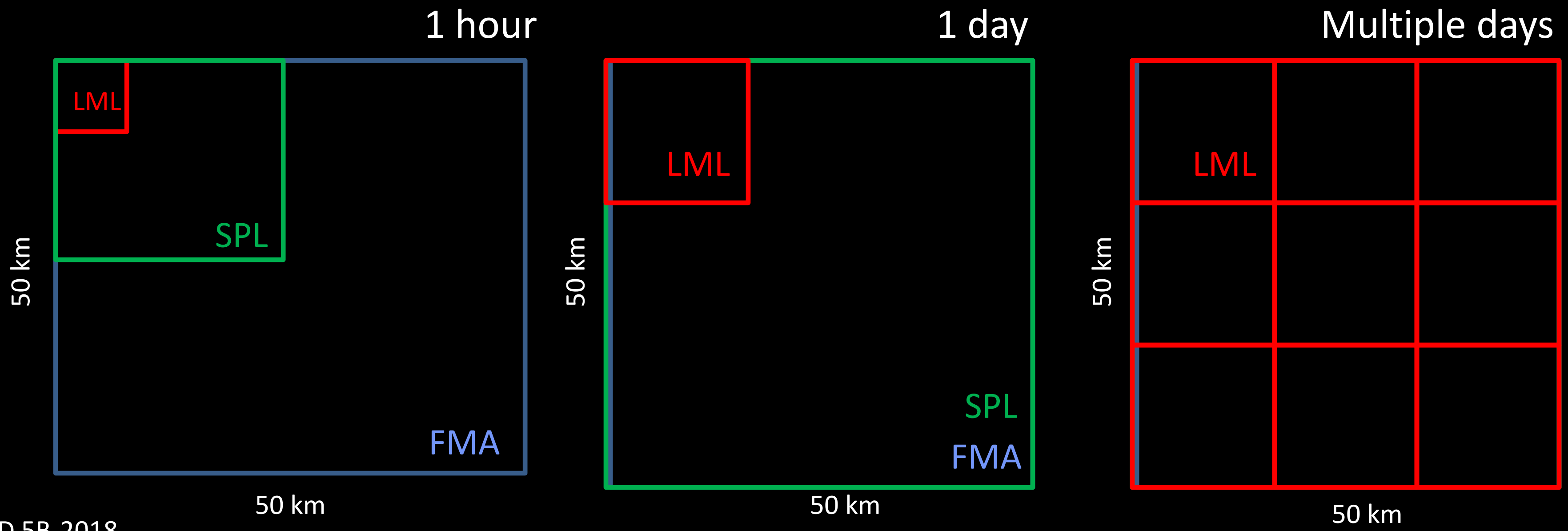
LML: 20 years to get from 10,000 pulses per second to 1 million pulses per second

Single Photon Lidar: Acquisition capacity

- Wästlund et al. 2018 (Sweden):
  - SPL covered 590 km^2/hour, LML covered 50 km^2/hour ()
- Mandleburger et al. 2019 (Austria):
  - Swath width for SPL was >2x greater that of LML, altitude was 5x greater
- Yu et al. 2020 (Finland):
  - SPL required 1/5th the number of flight lines required by LML

Single Photon Lidar: Acquisition capacity

Enables lidar acquisitions over very large areas with consistent parameters



High energy

Low frequency

LML versus SPL

Low energy

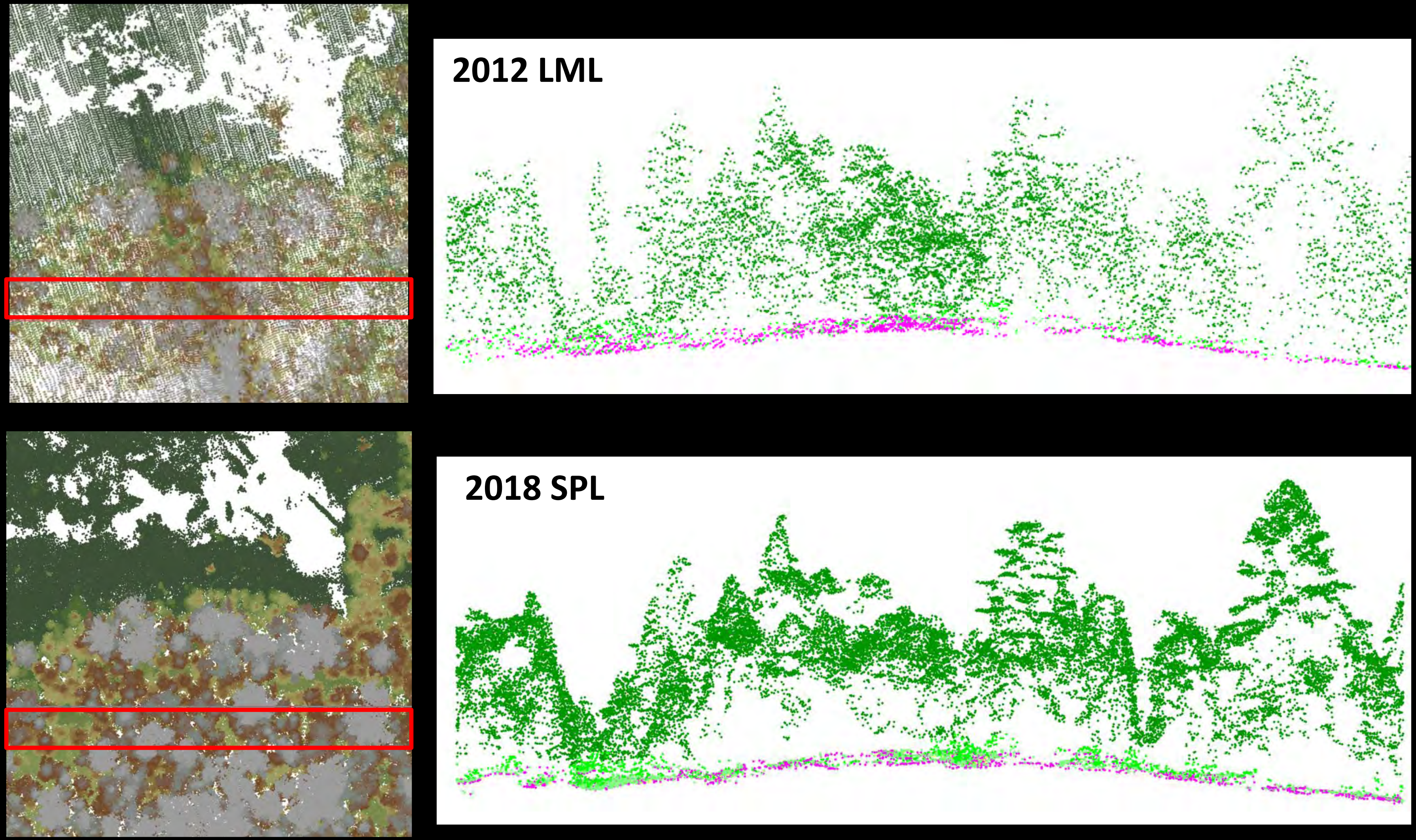
High frequency

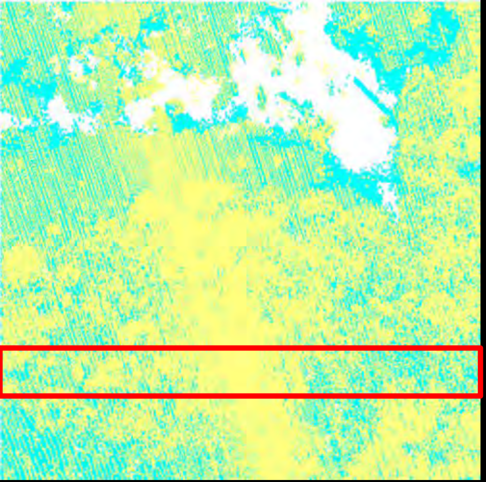
LML (Linear-Mode Lidar)

- 3D points clouds with low range noise (high precision)
- NIR wavelength (e.g. 1064 nm)
- Acquisition = low and slow
- Multiple returns for a single pulse
- Many photons to register a return = Multi-Photon Lidar (MPL)

SPL (Single Photon Lidar)

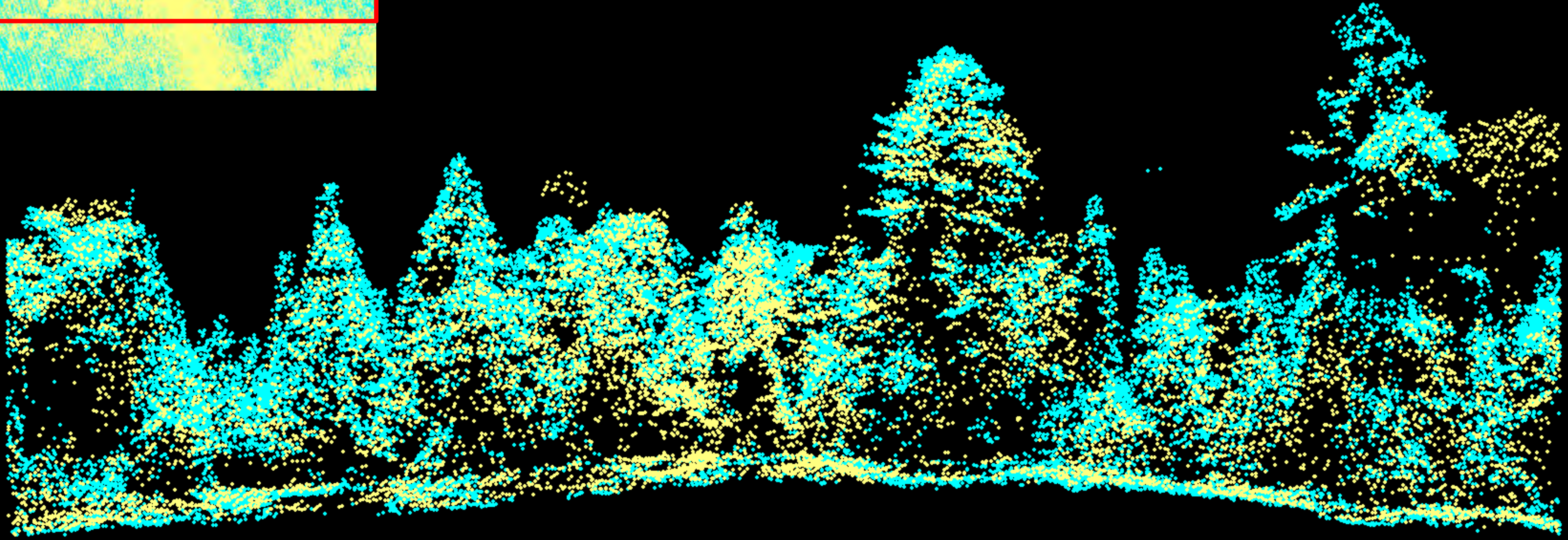
- High density 3D point clouds with high range noise (lower precision)
- Green wavelength (532 nm)
  - Greater sensitivity to background solar noise
  - Leaf reflectance is much reduced compared to NIR
- Acquisition = higher and faster
- Single photons = return = SPL


2012 LML
2018 SPL



Yellow = 2012 LML ANPD: ~5.8 pts/m^2

Blue = 2018 SPL ANPD: ~32.4 pts/m^2



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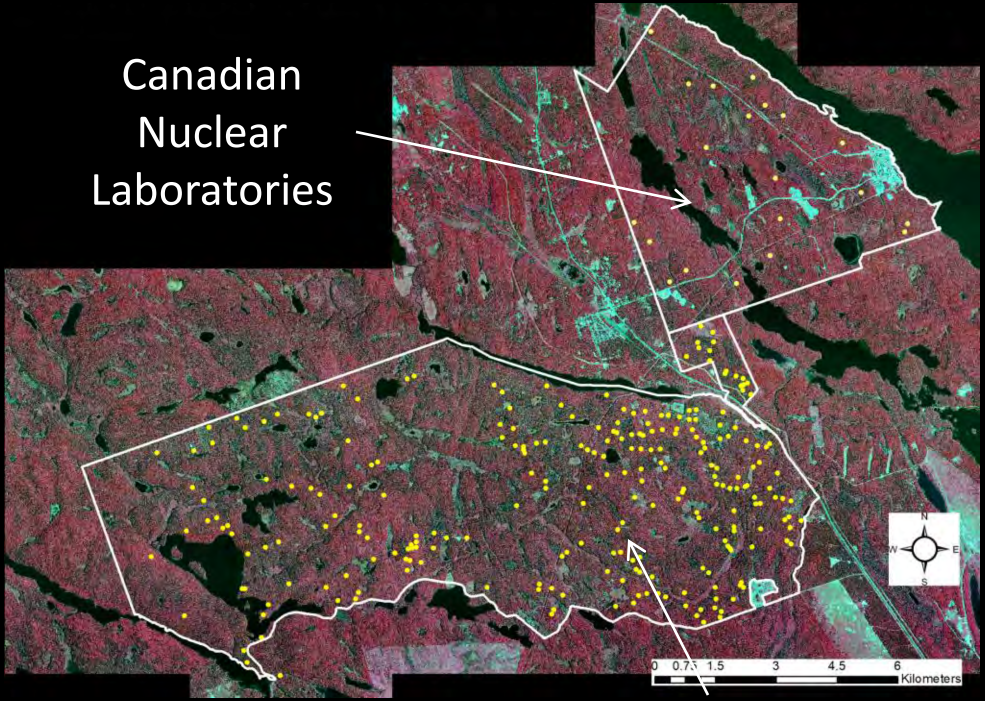
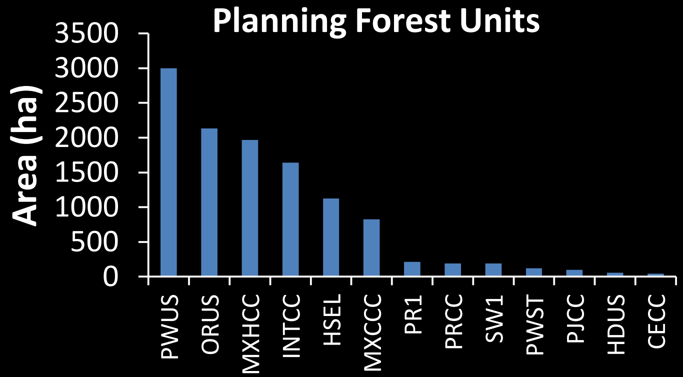
Study area: PRF and CNL

Canadian Nuclear Laboratories



Petawawa Research Forest

Source: M. Woods



Source: L.Cobb

Project objectives

1. Quantify the performance of single photon lidar (SPL) in an area-based approach to estimating forest inventory attributes;

2. Quantify the performance of SPL for characterizing terrain surface under varying forest types and canopy densities.

Assessing single photon lidar for enhanced forest inventory in diverse mixedwood forests

Joanne White[1], Margaret Penner[2], Murray Woods[3]

[1]Canadian Forest Service (Pacific Forestry Centre), Natural Resources Canada

[2]Forest Analysis Ltd.

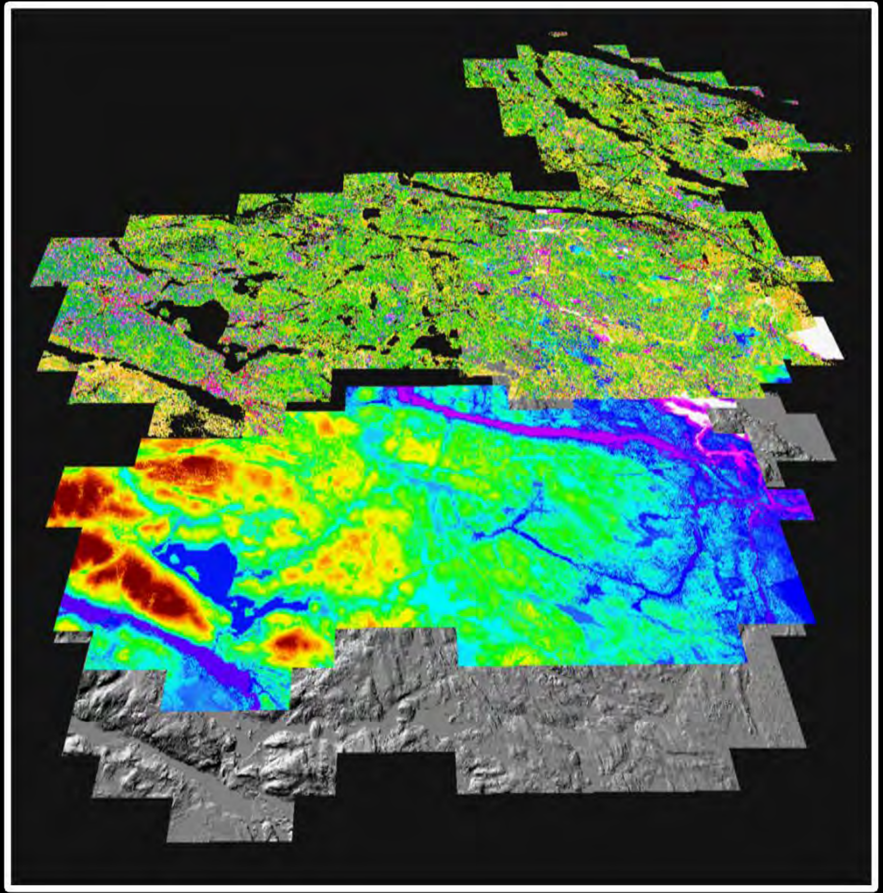
[3]Retired - Natural Resources Information Section, Science and Research Branch, Ontario Ministry of Natural Resources and Forestry

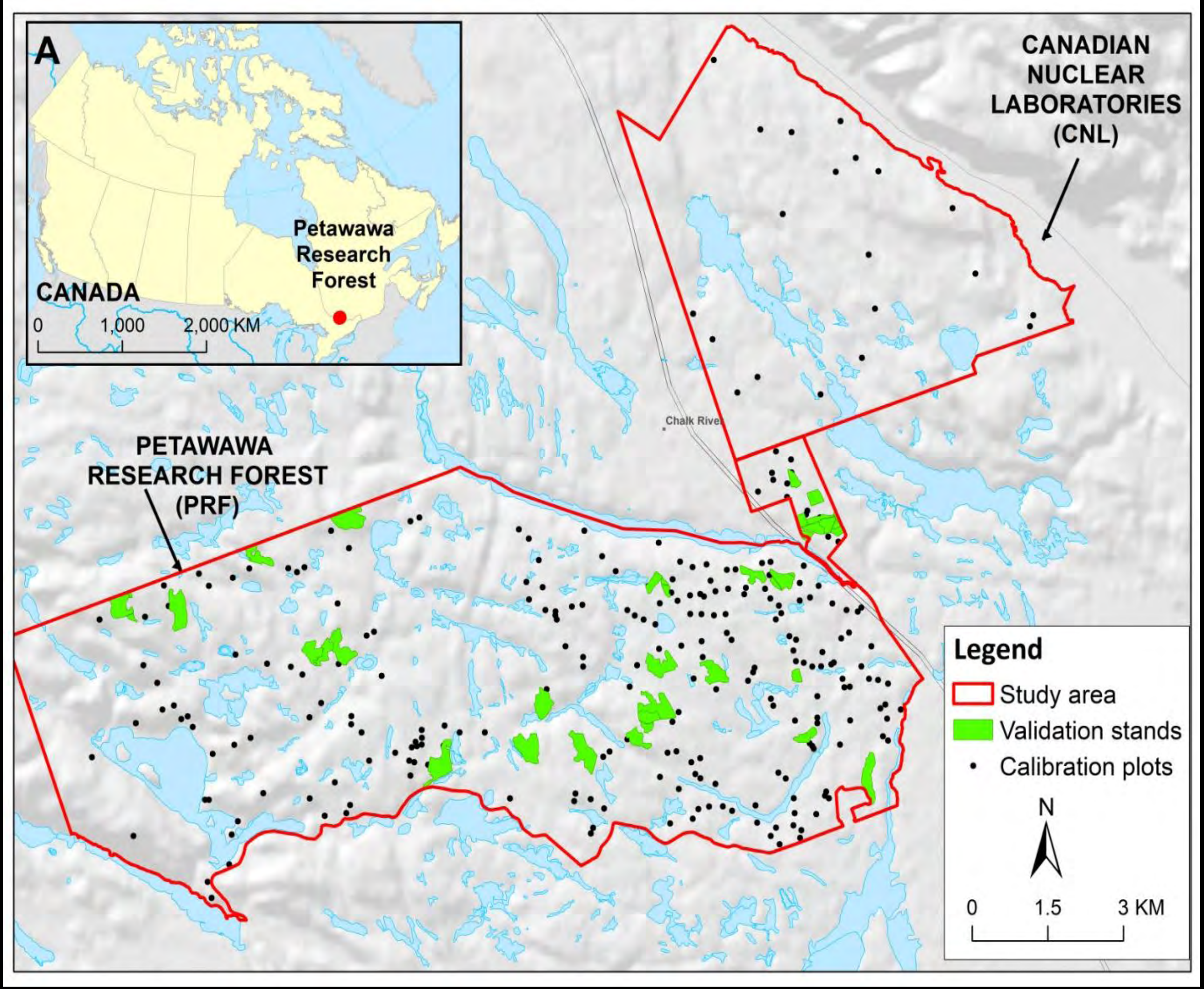
Research objectives (inventory)

- Assess the application of SPL data in an area-based approach to forest inventory in a temperate forest environment with a multitude of tree species and complex forest management histories;
- Determine how estimation accuracy varied by forest type using independent intensively sampled, stand-level validation data.

Study area: SPL data

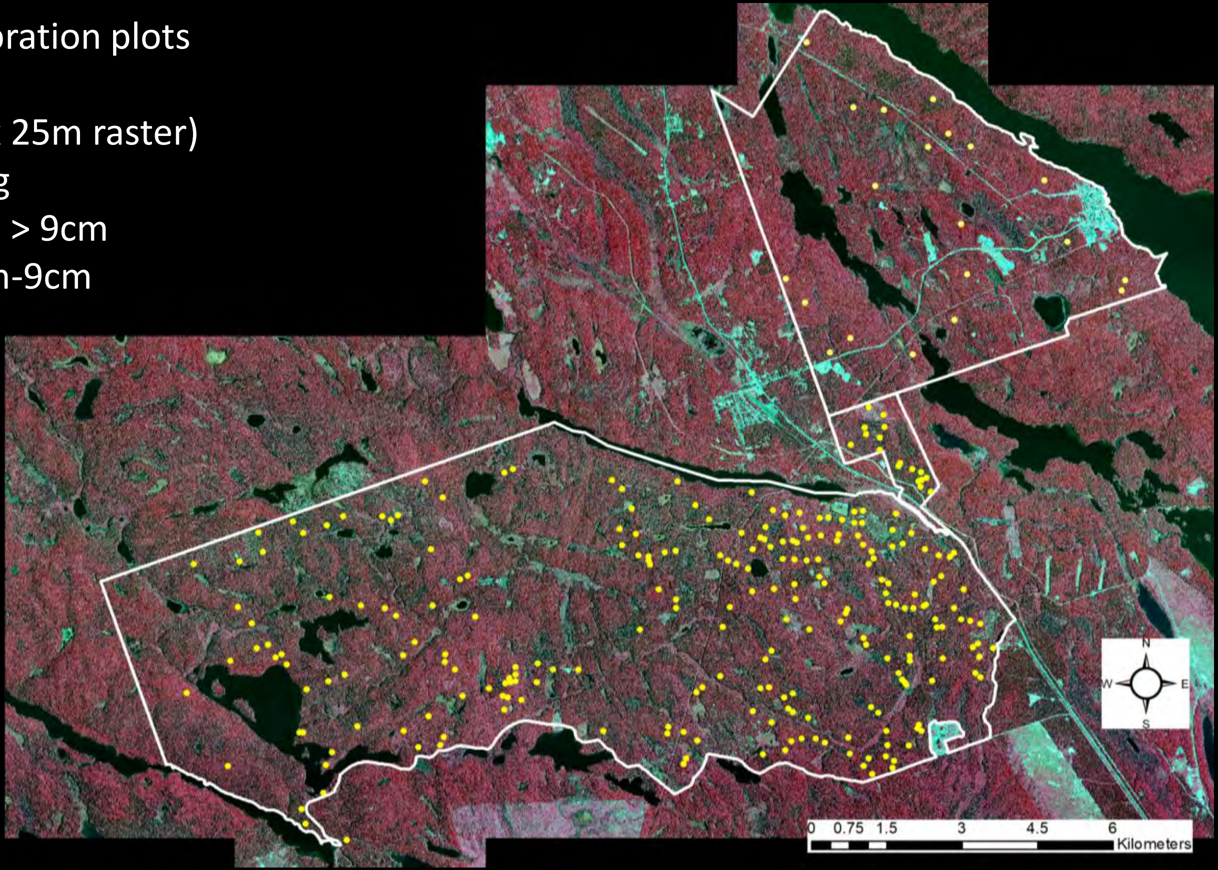
- Acquired: July 1, 2018
- Sensor: Leica SPL100
- Altitude: 3800 m
- ANPD: 32.8 points/m^2




A
CANADA
Petawawa
Research
Forest
0
1,000
2,000 KM
CANADIAN
NUCLEAR
LABORATORIES
(CNL)
Chalk River
PETAWAWA
RESEARCH FOREST
(PRF)
Legend
Study area
Validation stands
Calibration plots
N
0
1.5
3 KM

Calibration data

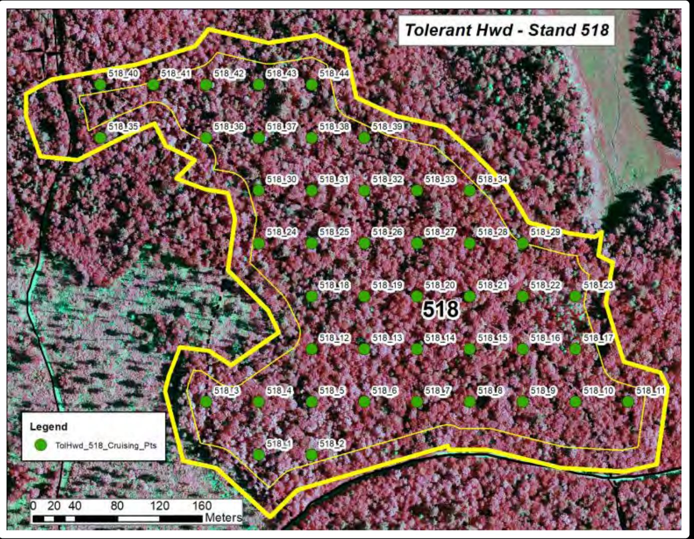
- 269 (249 PRF + 20 CNL) calibration plots
- Fixed-area plots
- 14.1m radius (625 m^2) (25 x 25m raster)
- Structurally-guided sampling
- Species, dbh, status, heights > 9cm
- Sub-sampled for trees 2.5cm-9cm
- Sub-metre GPS positioning

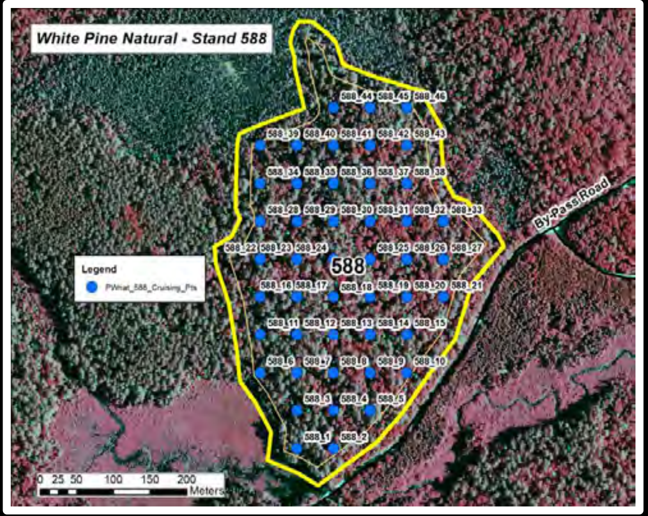


Validation data

- Independent, intensively sampled
- 27 stands cruised on a 50 m grid in spring 2019
- 10 forest types

4 X Pine Natural	4 X Red Pine Plant	3 X Tolerant Hwd	4 X Mixedwood
2 X Oak	2 X Black Spruce	1 X Lowland Conifer	2 X Jack Pine
2 X Poplar	3 X Pine Managed		





Target forest inventory attributes

Height

- Dominant/codominant height
- Top height
- Lorey's height ≥ 2.5 cm and ≥ 9.1 cm*

Average tree size

- Quadratic mean DBH ≥ 2.5 cm and ≥ 9.1 cm

Density

- Basal area ≥ 2.5 cm and ≥ 9.1 cm*
- Stems per ha ≥ 2.5 cm* and ≥ 9.1 cm*

Volumes

- Gross total volume ≥ 2.5 cm (TVOL)
- Gross total volume ≥ 9.1 cm (TVOL_merch)*
- Merchantable stem volume ≥ 9.1 cm (MVOL)*
- Total aboveground biomass ≥ 2.5 cm and ≥ 9.1 cm*

Ratios[1]

- VBAR_TVOL_ratio = VBAR_TVOL_merch/VBAR_TVOL
- VBAR_MVOL ratio = VBAR_MVOL/VBAR_TVOL_merch
- BA_merch_ratio = BA_merch/BA_all
- HL_merch_ratio = HL_merch/HL_all
- Bio_merch_ratio = BIO_merch/BIO_all

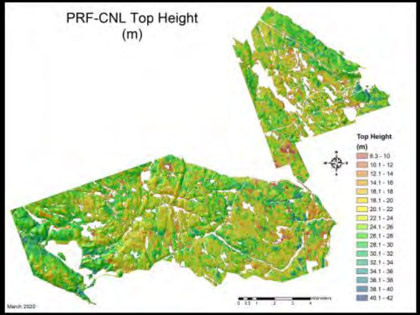
Management size class

- 4 size classes: poles, small, medium, large
- BA, QMD, TVOL_merch, MVOL, Biomass, VBAR, TPH

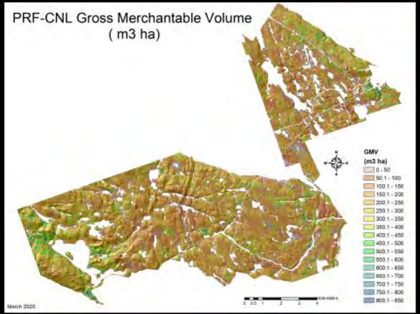
[1]Used to ensure logical estimates

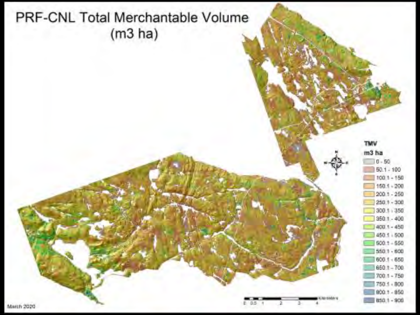
*Derived from other predicted attributes

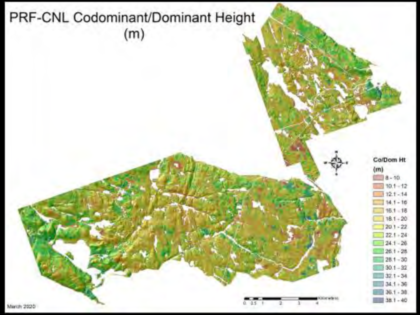
No forest type information used in modeling


PRF-CNL Top Height
(m)
Top Height
(m)
March 2020

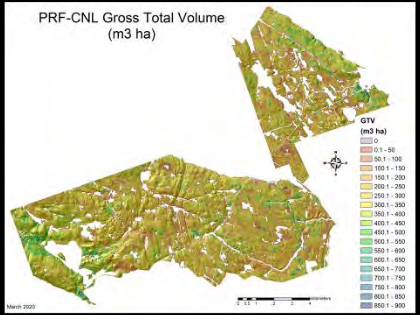

PRF-CNL Basal Area All
(m2 ha)
BA
m2 ha
March 2020


PRF-CNL Gross Merchantable Volume
(m3 ha)
GMV
(m3 ha)
March 2020

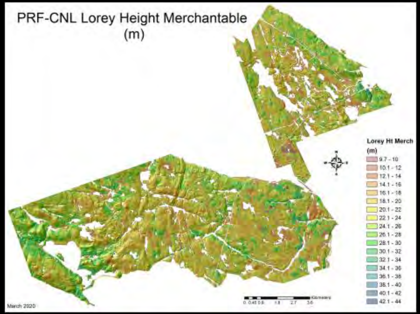

PRF-CNL Total Merchantable Volume
(m3 ha)
TMV
m3 ha
March 2020

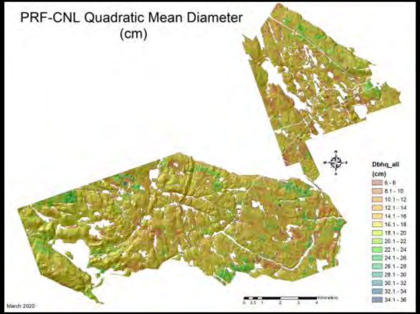

PRF-CNL Codominant/Dominant Height
(m)
Co/Dom Ht
(m)
March 2020


PRF-CNL Basal Area Merchantable
(m2 ha)
BA_merch
m2 ha
March 2020

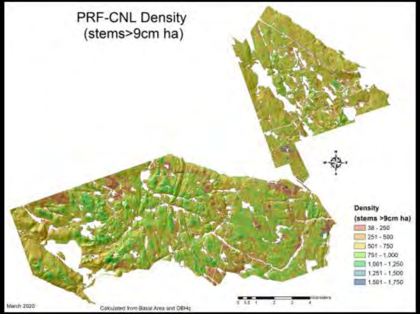

PRF-CNL Gross Total Volume
(m3 ha)
GTV
(m3 ha)
March 2020


PRF-CNL Merchantable Quadratic
Mean Diameter (cm)
dbhq_merch
cm
March 2020


PRF-CNL Lorey Height Merchantable
(m)
Lorey Ht Merch
(m)
March 2020


PRF-CNL Quadratic Mean Diameter
(cm)
Dbhq_all
(cm)
March 2020


PRF-CNL Merchantable Above Ground
Biomass (kg ha)
Merch Biomass
(kg ha)
March 2020


PRF-CNL Density
(stems>9cm ha)
Density
(stems >9cm ha)
March 2020
Calculated from Basal Area and DBHq

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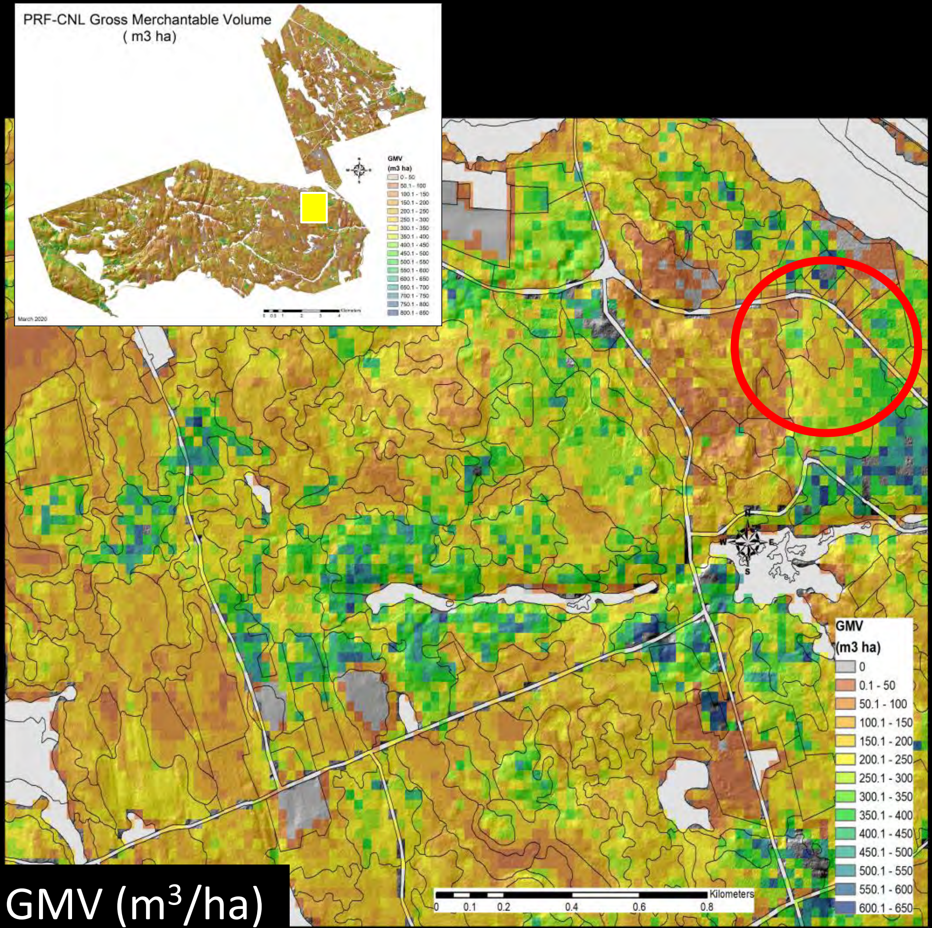
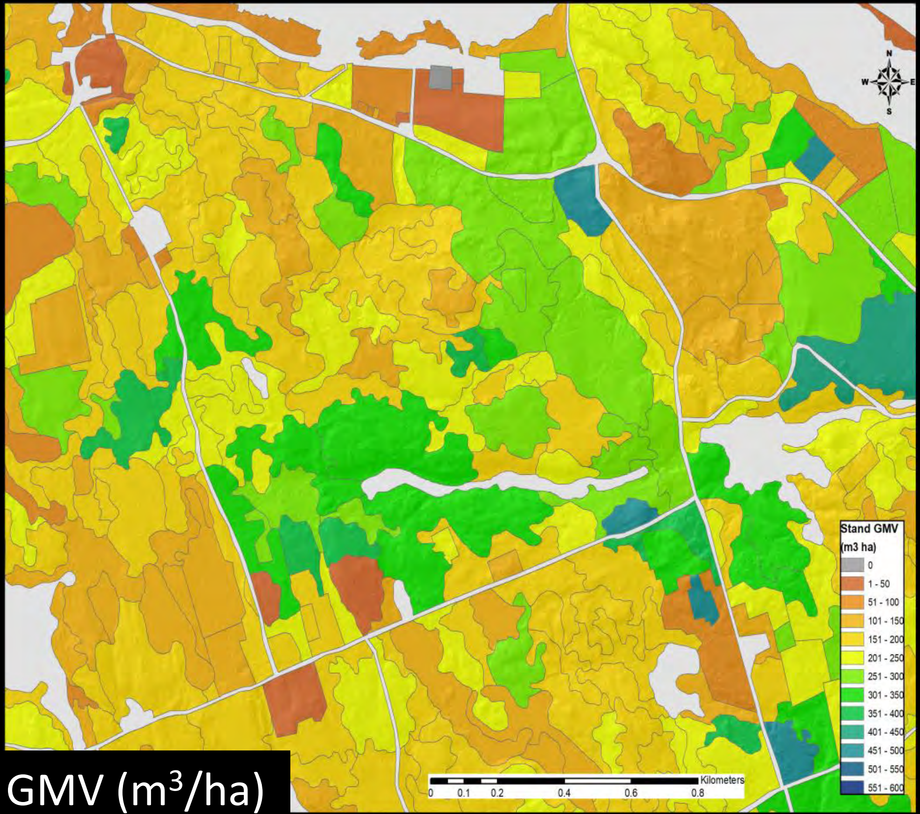
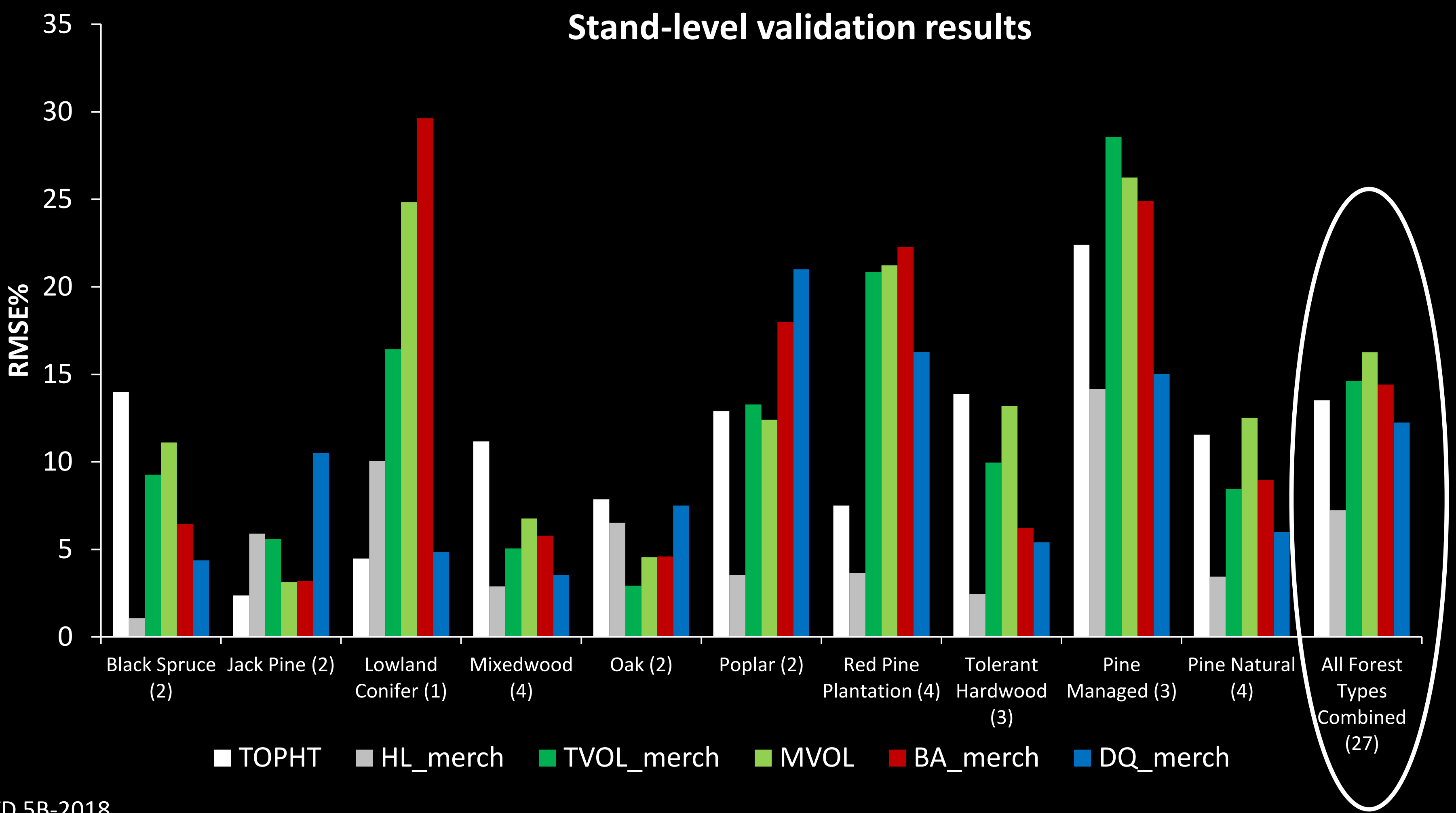




Raster predictions providing fine-scale resolution of landscape variation

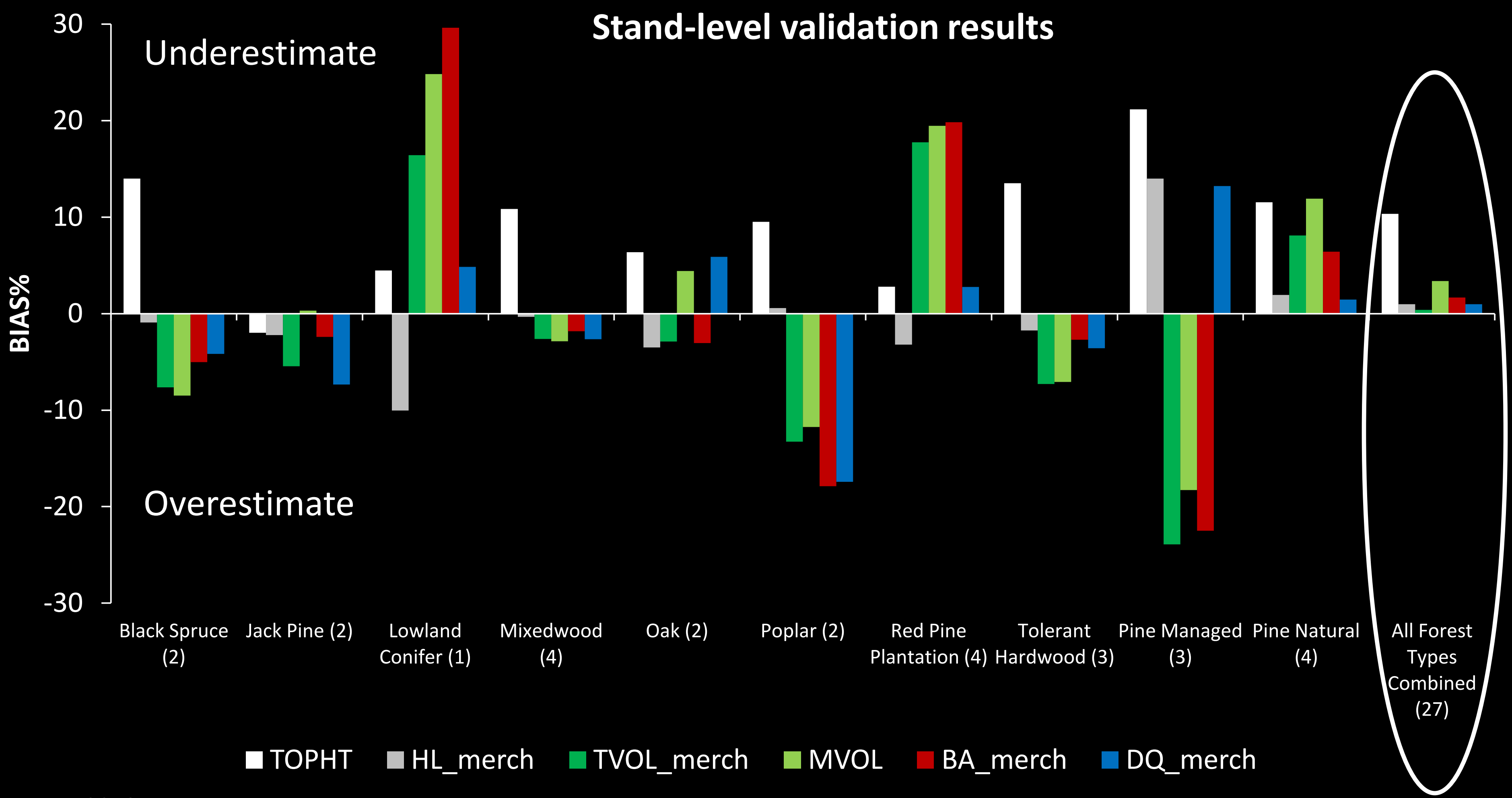
Mean stand polygon representation of raster predictions

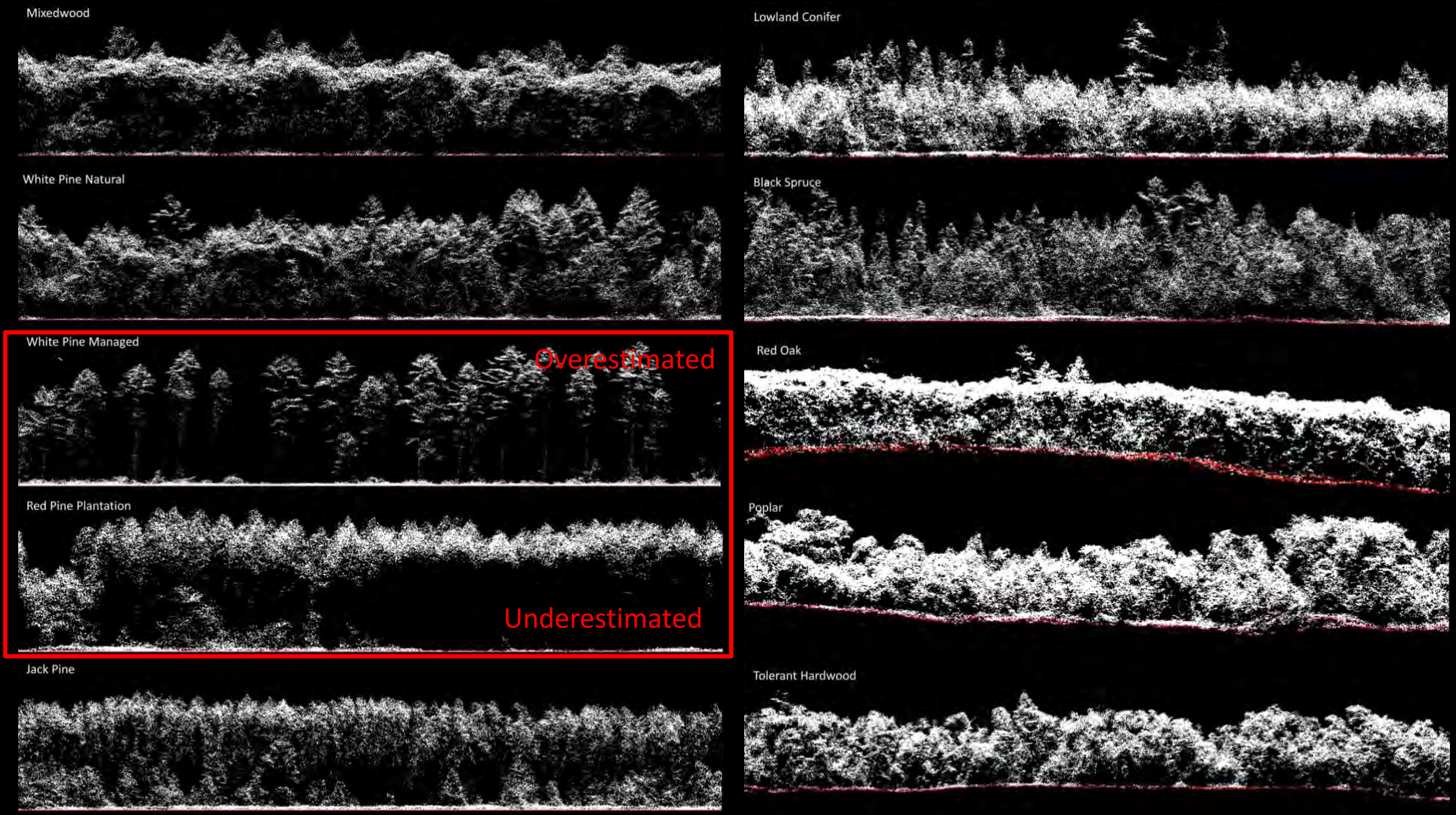
KTTD 5B-2018



Stand-level validation results
RMSE%
35
30
25
20
15
10
5
0
Black Spruce (2)
Jack Pine (2)
Lowland Conifer (1)
Mixedwood (4)
Oak (2)
Poplar (2)
Red Pine Plantation (4)
Tolerant Hardwood (3)
Pine Managed (3)
Pine Natural (4)
All Forest Types Combined (27)
TOPHT
HL_merch
TVOL_merch
MVOL
BA_merch
DQ_merch

KTTD 5B-2018


Stand-level validation results
Underestimate
Overestimate
BIAS%
30
20
10
0
-10
-20
-30
Black Spruce (2)
Jack Pine (2)
Lowland Conifer (1)
Mixedwood (4)
Oak (2)
Poplar (2)
Red Pine Plantation (4)
Tolerant Hardwood (3)
Pine Managed (3)
Pine Natural (4)
All Forest Types Combined (27)
TOPHT
HL_merch
TVOL_merch
MVOL
BA_merch
DQ_merch



Mixedwood
Lowland Conifer
White Pine Natural
Black Spruce
White Pine Managed
Overestimated
Red Oak
Red Pine Plantation
Poplar
Underestimated
Jack Pine
Tolerant Hardwood

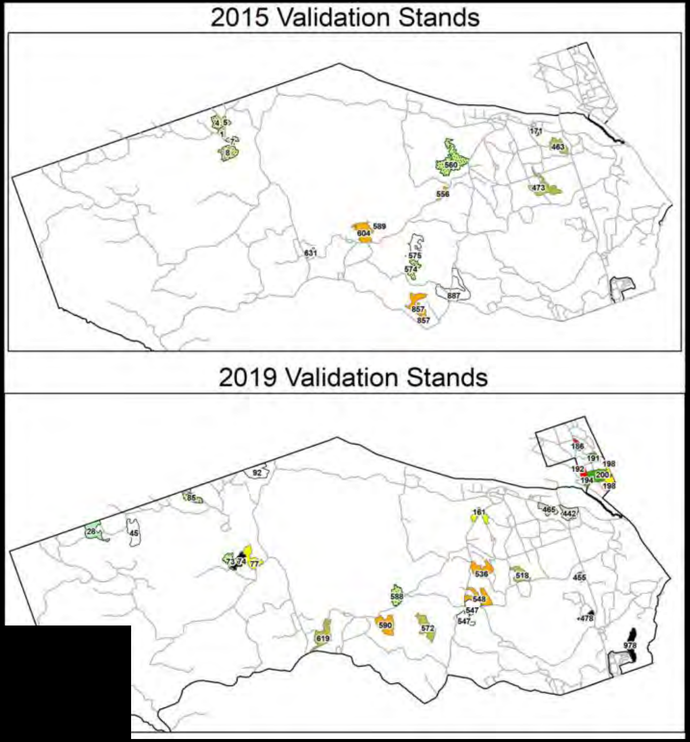
KTTD 5B-2018

EFI outcomes: 2012 LML vs 2018 SPL

2012 Validation:

- 17 stands cruised on a 50m grid in 2015
- No sampling stratification - Stands were selected to meet operational requirements for planned harvesting activities
- Unbalanced sample by forest type (5 types sampled)

8 X Pine Natural	1 X Red Pine Plant	3 X Tolerant Hwd	3 X Mixedwood
2 X Oak			

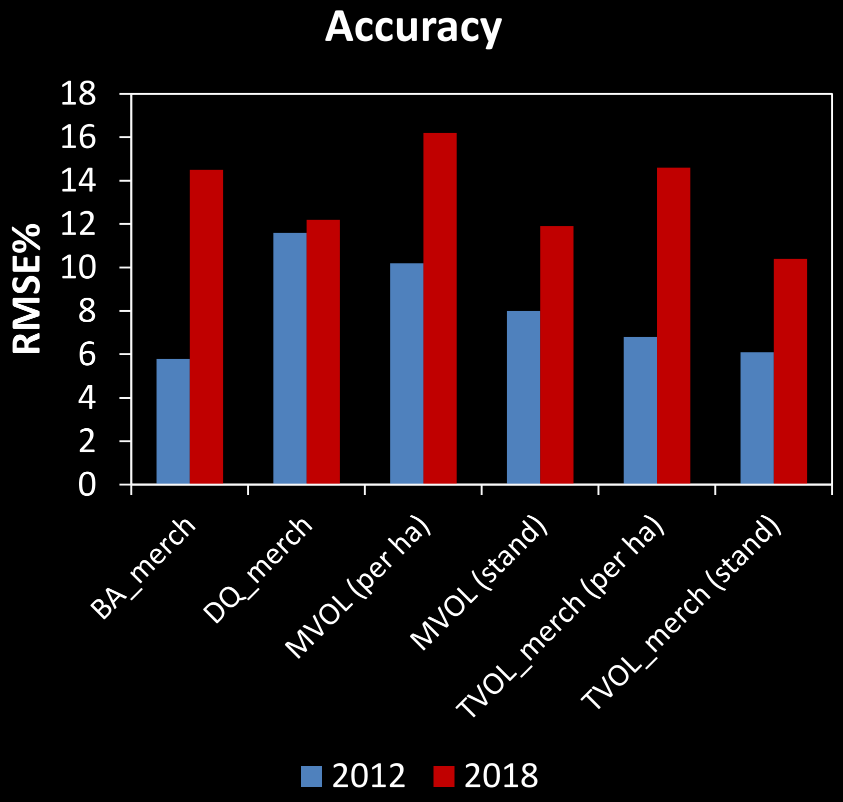


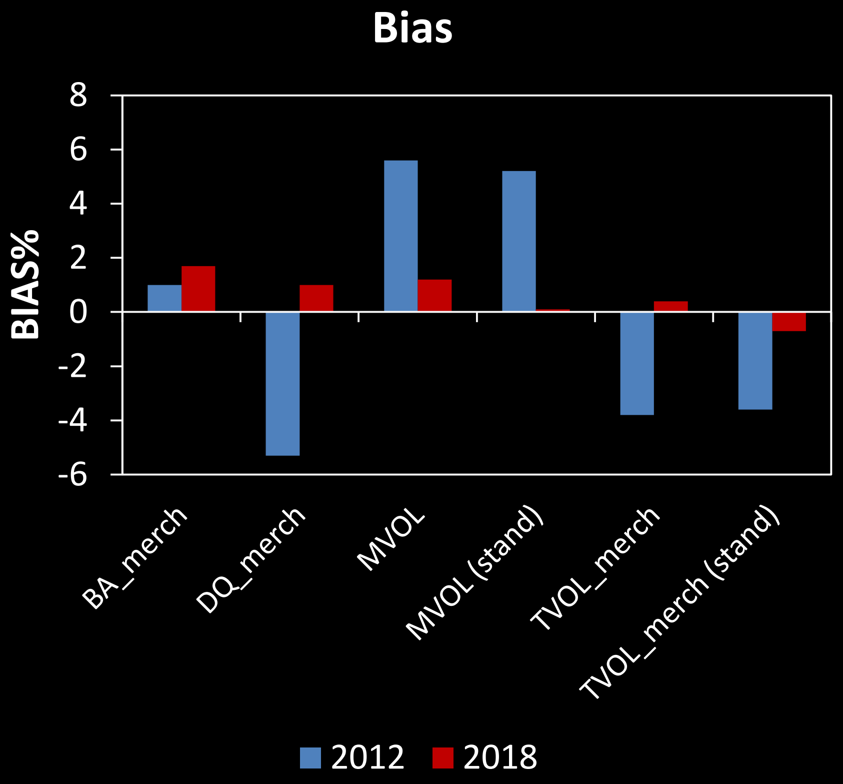
2018 Validation:

- 27 stands cruised on a 50m grid in spring 2019 (0 years post LiDAR acquisition)
- 10 forest types x 3 stands identified. Post-cruising species information realigned sampling by forest types

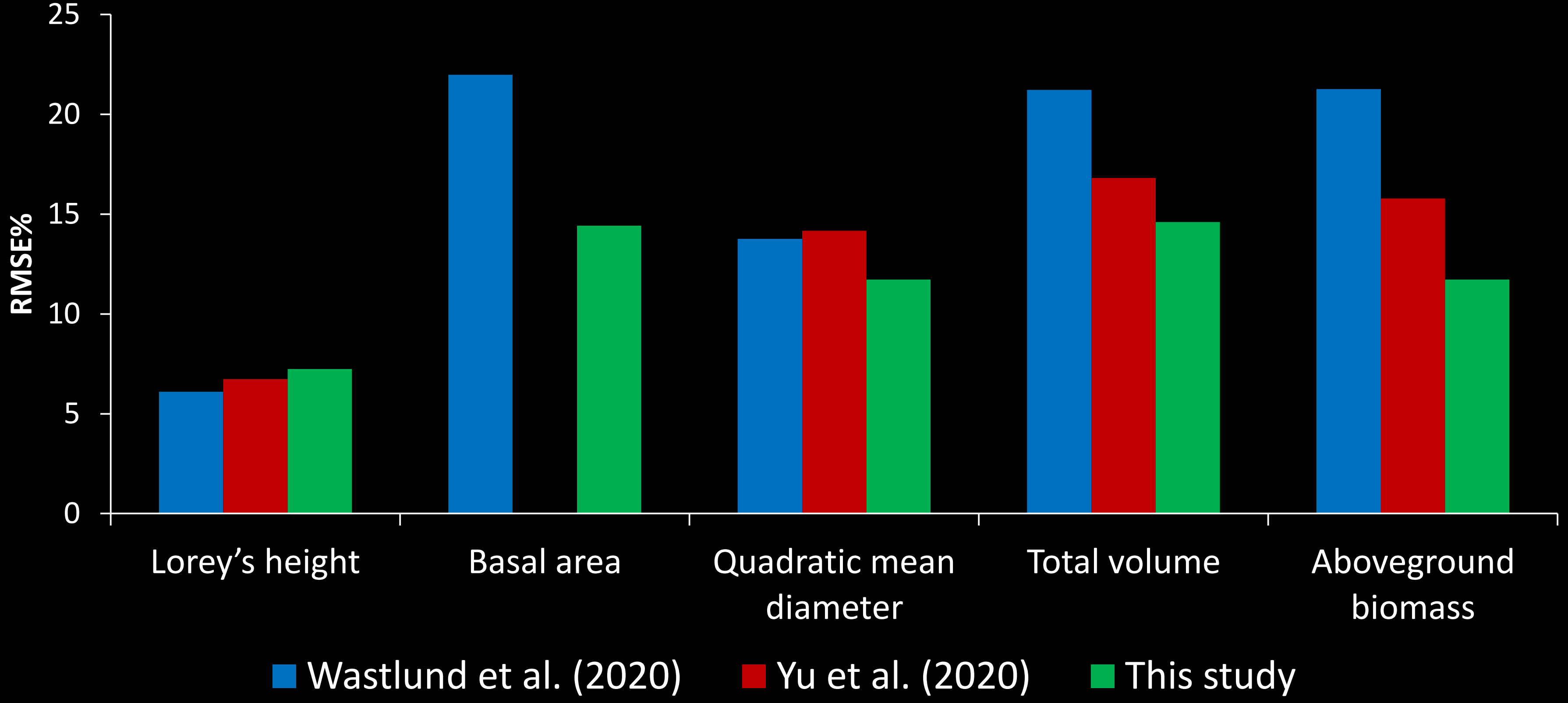
4 X Pine Natural	4 X Red Pine Plant	3 X Tolerant Hwd	4 X Mixedwood
2 X Oak	2 X Black Spruce	1 X Lowland Conifer	2 X Jack Pine
2 X Poplar	3 X Pine Managed		

EFI outcomes: 2012 LML vs 2018 SPL

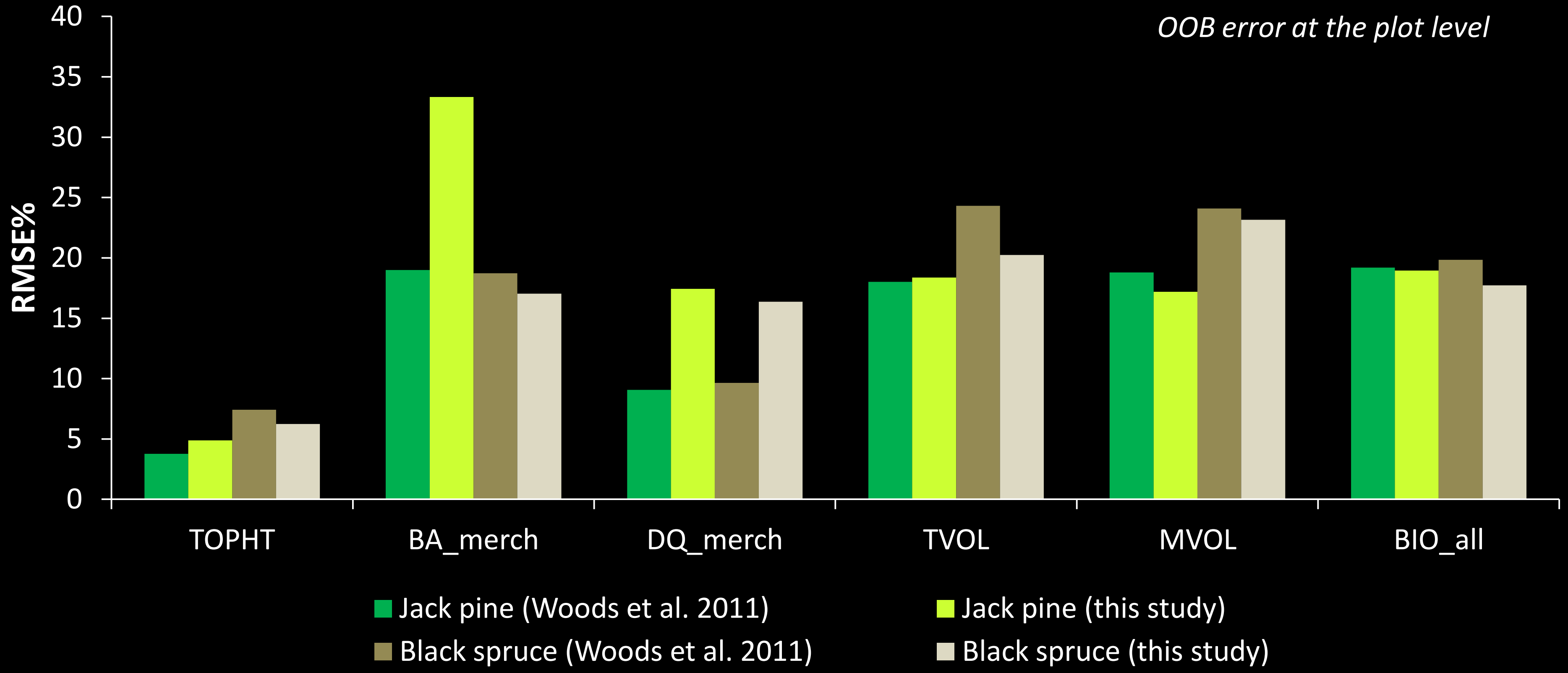




EFI outcomes: Comparisons to other studies

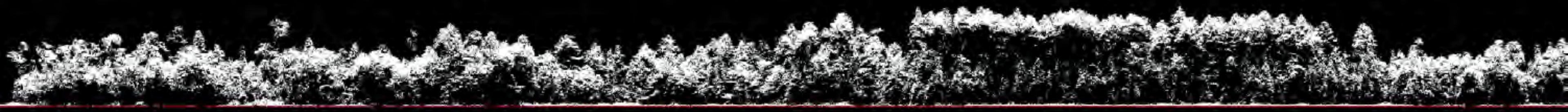


EFI outcomes: Comparisons to other studies



Summary (inventory)

- Area-based models developed using SPL data produced accurate inventory attribute estimates with minimal bias
- Accuracy of attribute estimates are on par with those generated using LML
- Accuracy varies by forest type, with greatest overestimation for managed white pine stands and the greatest underestimation for red pine plantations
- Accuracy for boreal forest types (jack pine, black spruce) similar to those reported in other studies



White, J.C., Penner, M., Woods, M. 2021. Assessing single photon lidar for operational implementation of an enhanced forest inventory in diverse mixedwood forests. *The Forestry Chronicle*. IN PRESS

Open Access


Assessing single photon LiDAR for operational implementation of an enhanced forest inventory in diverse mixedwood forests

by Joanne C. White[1*], Margaret Penner[2] and Murray Woods[3]

ABSTRACT
Airborne laser scanning (ALS; LiDAR) data are an increasingly common data source for forest inventories, and approaches integrating ALS data with field plot measurements have become operational in several jurisdictions. As technology continues to evolve, different LiDAR sensors can provide new opportunities to incorporate LiDAR data into forest inventory workflows. Single photon LiDAR (SPL) enables efficient, large area data acquisition and merits further investigation for forest inventory applications. Herein, we investigated the capacity of leaf-on SPL data, combined with 269 field plots, for estimating forest inventory attributes in the Great Lakes–St. Lawrence mixedwood forests of southern Ontario, Canada. Inventory attribute estimates were validated at the stand level using independent reference data acquired for 27 intensively sampled stands. Top height, Lorey's height, gross total volume for merchantable stems, merchantable stem volume, basal area, quadratic mean diameter, and total aboveground biomass were estimated with a relative RMSE of 13.52%, 7.24%, 14.61%, 16.27%, 14.42%, 12.25%, and 11.72%, respectively. Relative bias was < 1% for all attributes except top height (10.34%), merchantable volume (3.37%), and basal area (1.68%). Accuracy and bias varied by forest type and stand-level validation was important for assessing model performance in different stand conditions. SPL data can be used to generate accurate, area-based forest inventories in mixedwood forests that have a multitude of tree species and complex forest management histories.

Keywords: enhanced forest inventory, LiDAR, temperate forest, ALS, SPL, EFI, PRF

RÉSUMÉ IN TRANSLATION

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[2]Forest Analysis Ltd., 1188 Walker Lake Dr., RR4, Huntsville, ON P1H 2J6, Canada
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KTTD 5B-2018

Project objectives

1. Quantify the performance of single photon lidar (SPL) in an area-based approach to estimating forest inventory attributes;

2. Quantify the performance of SPL for characterizing terrain surface under varying forest types and canopy densities.

Evaluating the capacity of single photon lidar for terrain characterization under vegetation canopy

Joanne White[1], Murray Woods[2], Thomas Krahn[3], Charles Papasodoro[4], David Bélanger[4], Craig Onafrychuk[3], Ian Sinclair[5]

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[5]Natural Resources Information Section, Science and Research Branch, Ontario Ministry of Natural Resources and Forestry, Ontario Forest Research Institute

Research objectives (terrain)

1. Quantify the vertical accuracy and precision of SPL data (leaf-on and leaf-off) for characterizing terrain surface elevations under a range of forest conditions and acquisition altitudes (3800 m versus 2000 m)

2. Evaluate derived DEMs

Lidar data

Leaf-on

Leaf-off

2012 LML

2019H SPL

Acquired at 3800 m

2018 SPL

2019L SPL

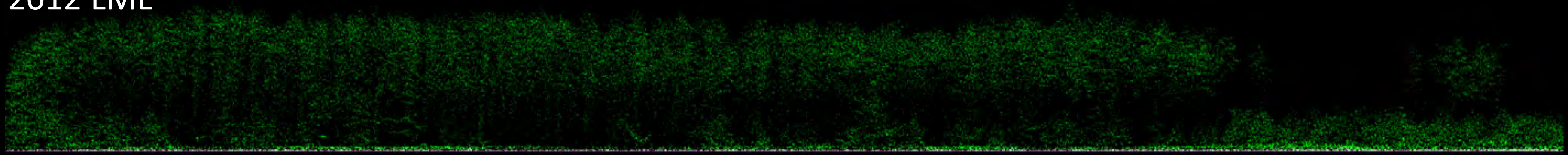
Acquired at 2000 m

KTTD 5B-2018

Lidar data

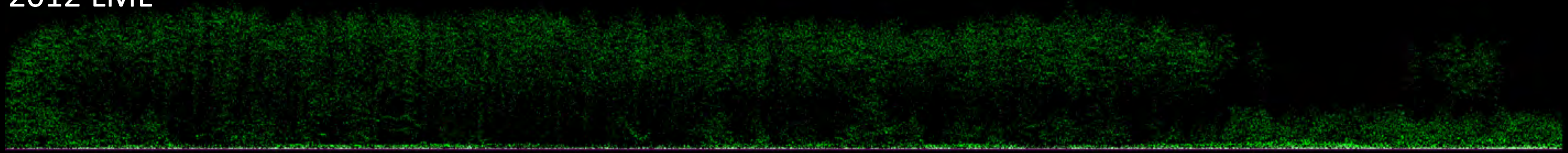
Parameter	2012 LML	2018 SPL	2019H SPL	2019L SPL
Acquisition conditions (leaf-on or leaf-off)	Leaf-on	Leaf-on	Leaf-off	Leaf-off
Sensor	Riegl 680i	Leica SPL100	Leica SPL100	Leica SPL100
Average flying altitude (m AGL)	750	3760	3760	2000
Average flying speed (knots)	<100	<180	<180	<160
Swath Width (m)	~600–700	2000	2000	1000
Aggregate Nominal Pulse density (pulses/m^2)	5.8	32.4	28.6	51.4
Average ground pulse density (pulses/m^2)	1.3	2.8	3.8	5.5
Percentage of returns that are first returns only	17.1	88.3	58.4	46.4
Ratio of first returns to second returns	1.6	17.8	4.1	2.92

2012 LML

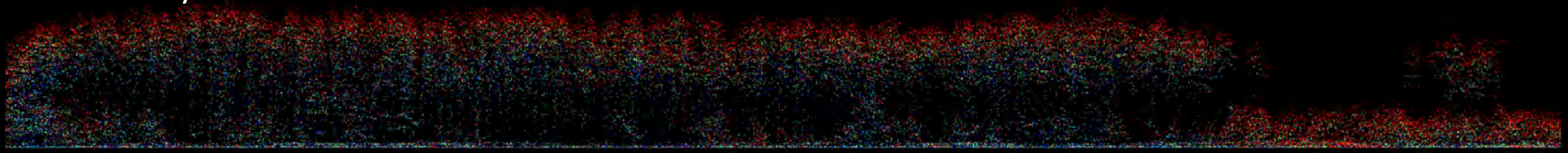


2012 LML by return

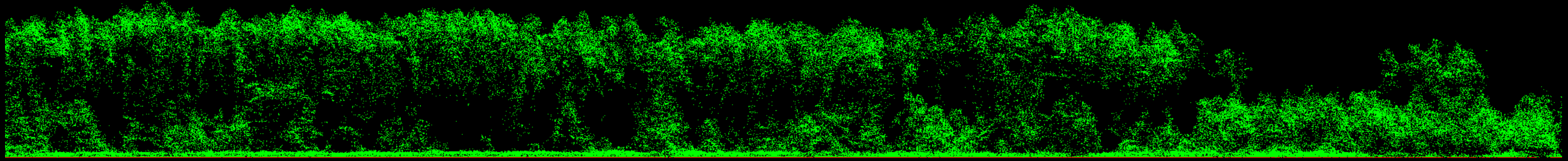
2012 LML



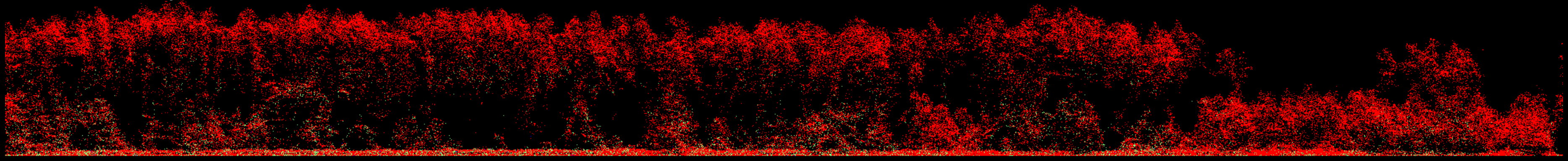
2012 LML by return

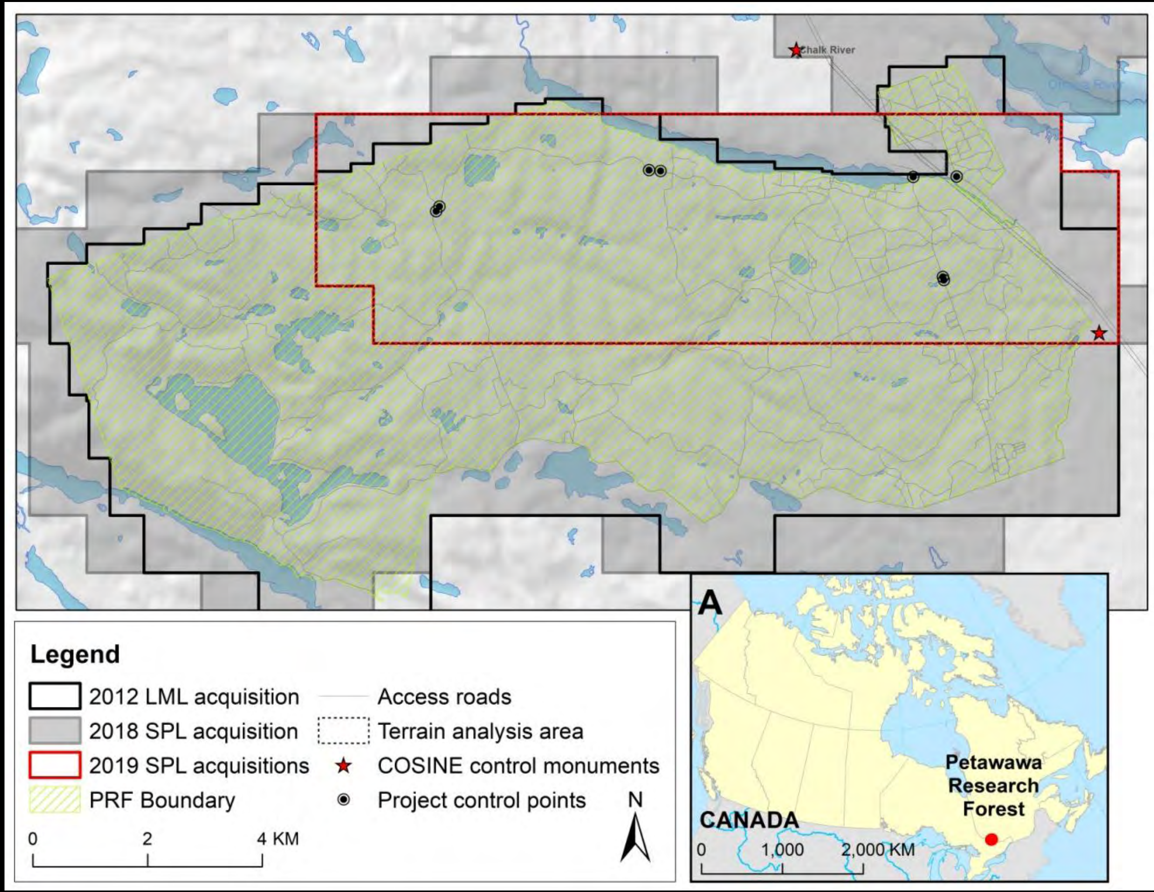


2018 SPL



2018 SPL by return



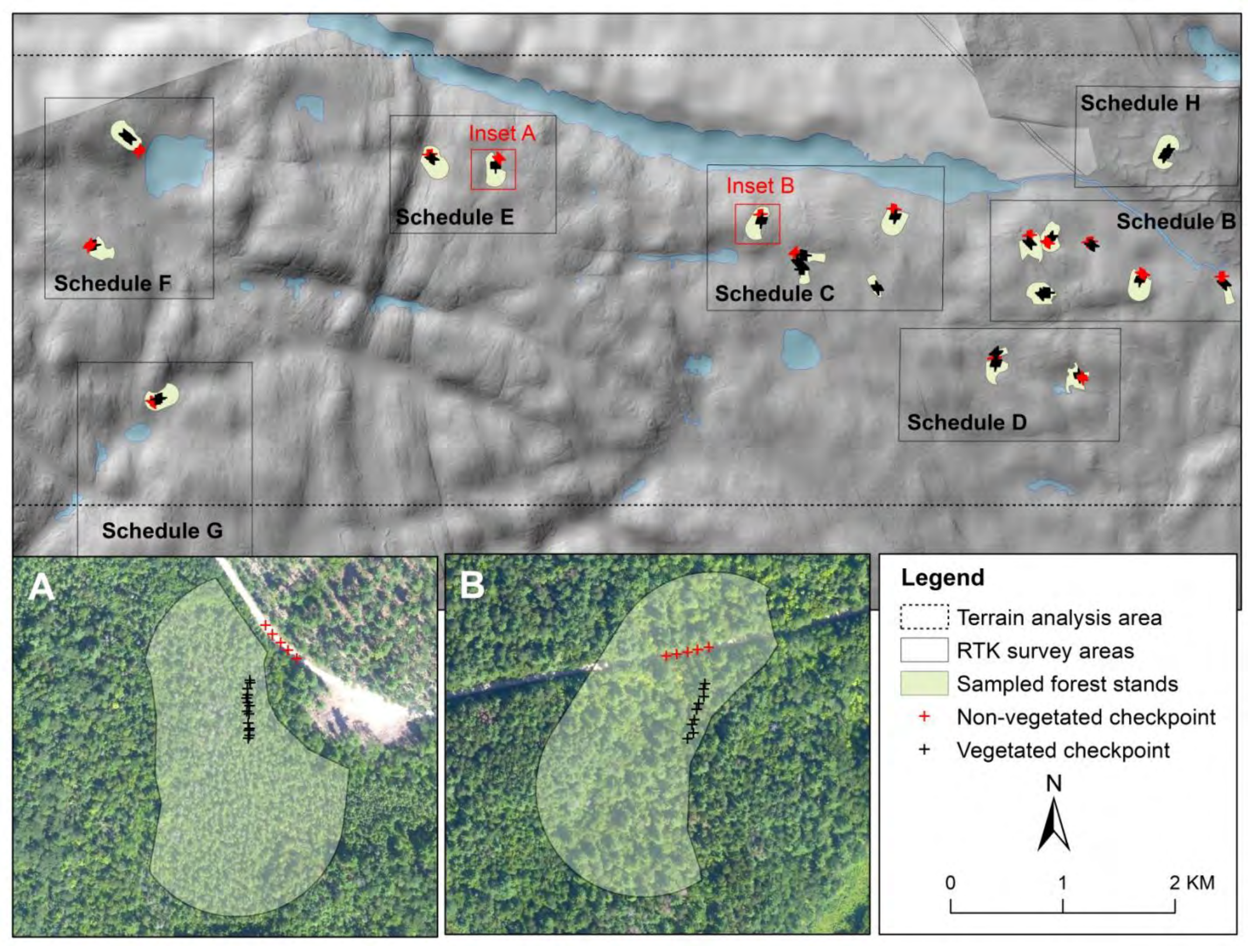

Chalk River
Legend
2012 LML acquisition
2018 SPL acquisition
2019 SPL acquisitions
PRF Boundary
Access roads
Terrain analysis area
COSINE control monuments
Project control points
0
2
4 KM
N
A
Petawawa Research Forest
CANADA
0
1,000
2,000 KM

KTTD 5B-2018

Reference data for terrain evaluation

- Real-Time Kinematic (RTK) survey
- 299 checkpoints in a range of cover types

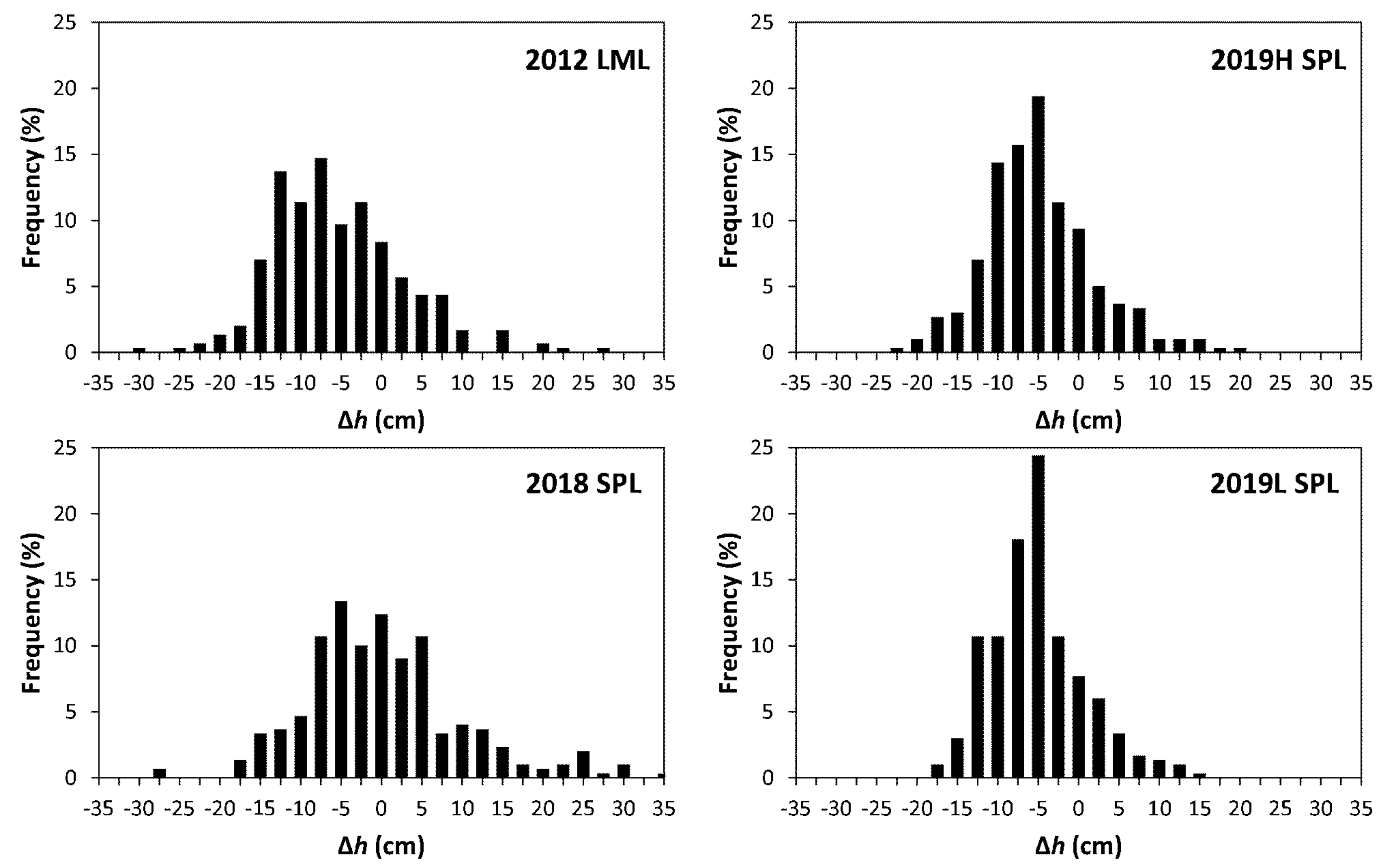
Generalized Cover Type	Number of checkpoints	Detailed Cover Type	Number of checkpoints
Non-vegetated	79	Asphalt	32
		Gravel	47
Vegetated	220	Black Spruce	37
		Coniferous Plantation	21
		Intolerant Hardwood	37
		Jack Pine	15
		Low Vegetation	14
		Mixedwood	34
		Red and White Pine	27
		Tolerant Hardwood	35


Inset A
Inset B
Schedule H
Schedule E
Schedule B
Schedule F
Schedule C
Schedule D
Schedule G
A
B
Legend
Terrain analysis area
RTK survey areas
Sampled forest stands
Non-vegetated checkpoint
Vegetated checkpoint
N
0
1
2 KM

KTTD 5B-2018

Results (checkpoints)

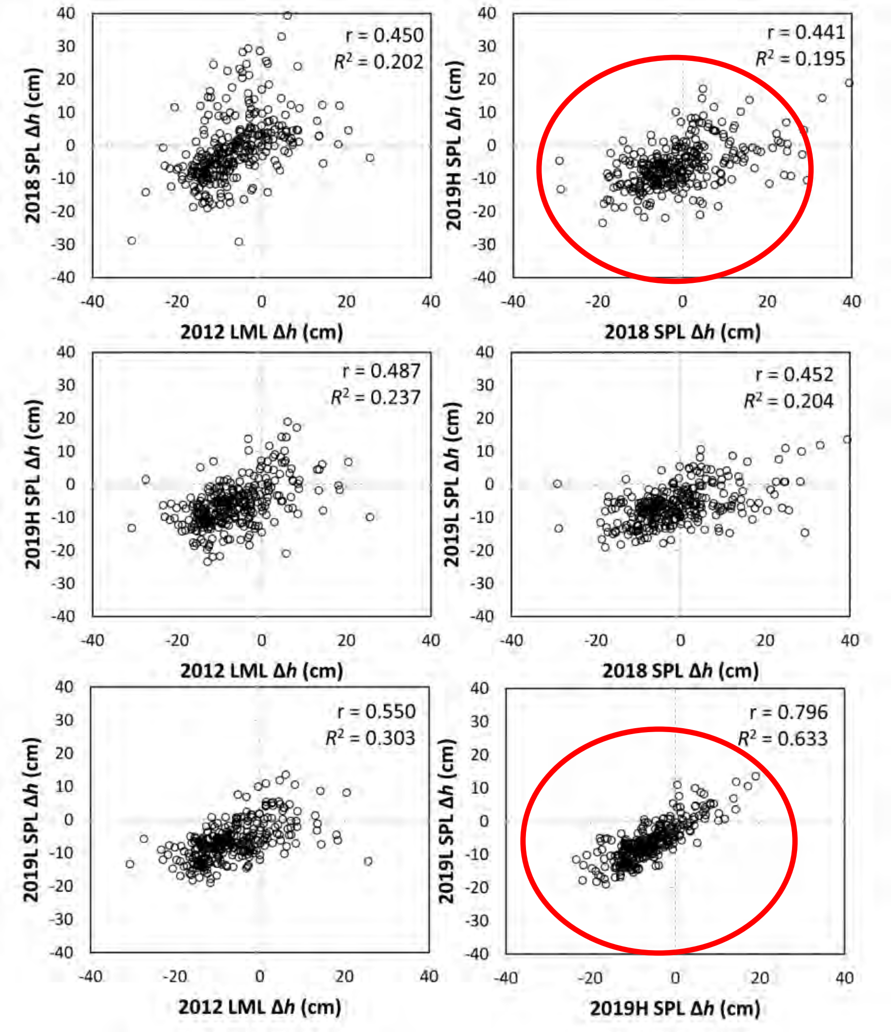
(Lidar z – Reference z)



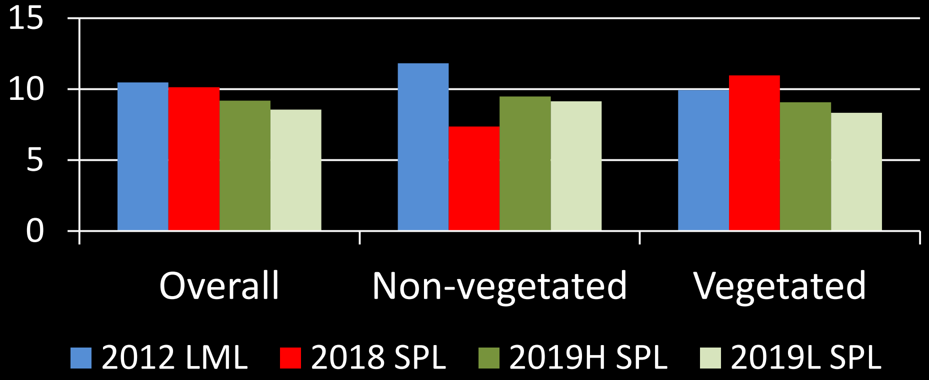
KTTD 5B-2018

Results (checkpoints)

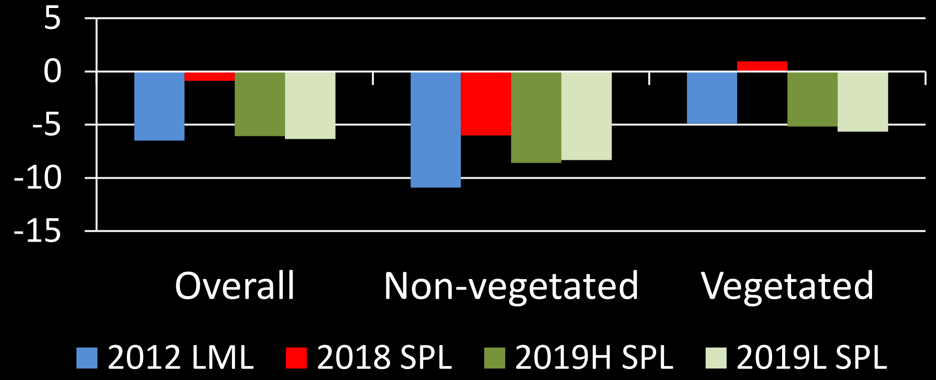
- Do we see the same error, of the same magnitude and direction (positive or negative), at the same location?



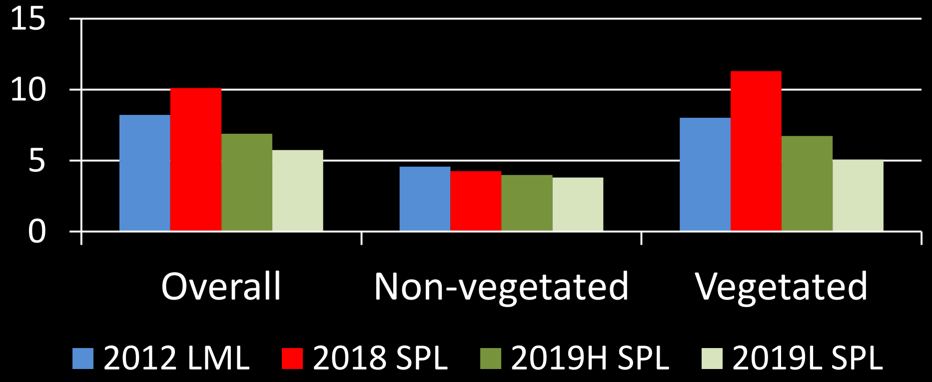
RMSE (cm)



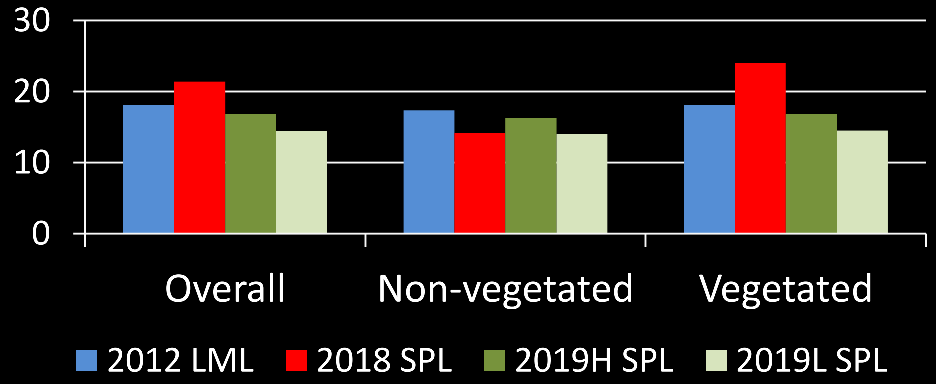
Mean Error (cm)



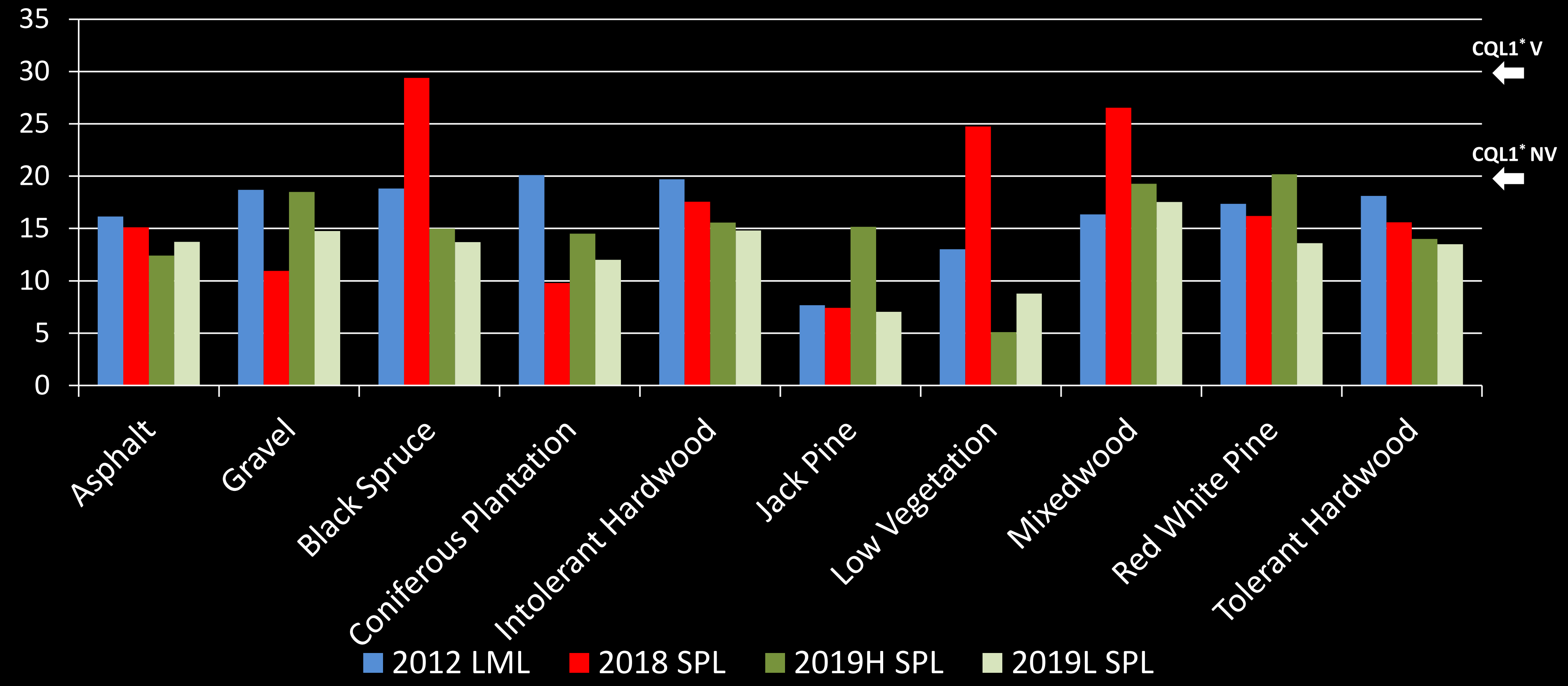
Error Standard Deviation (cm)



95th Percentile (cm)

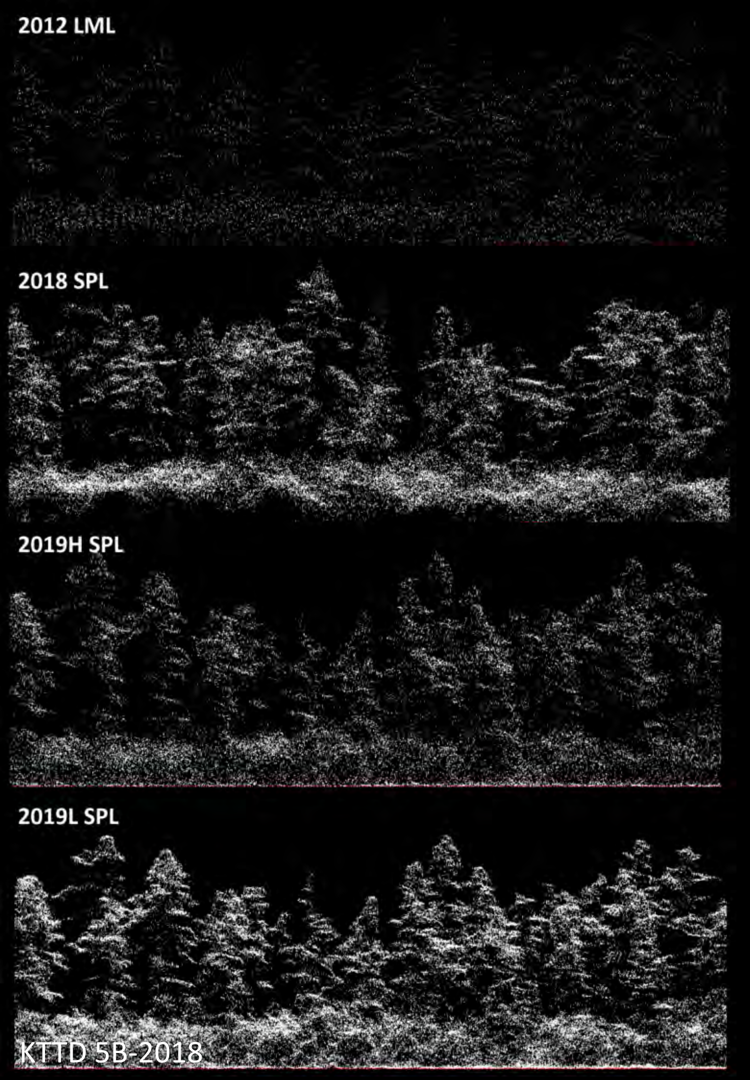


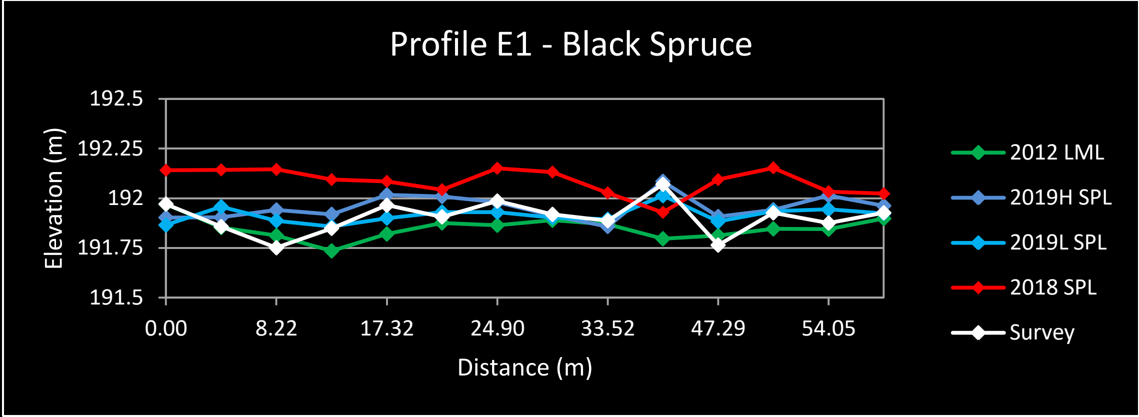
95th Percentile (cm)



*Canadian Quality Level 1 (CQL1) Key Requirements for Topographic Base Mapping

KTTD 5B-2018


2012 LML
2018 SPL
2019H SPL
2019L SPL
KTTD 5B-2018


Profile E1 - Black Spruce
Elevation (m)
192.5
192.25
192
191.75
191.5
0.00
8.22
17.32
24.90
33.52
47.29
54.05
Distance (m)
2012 LML
2019H SPL
2019L SPL
2018 SPL
Survey

Results (wall-to-wall DEM comparison)

2012 - 2018

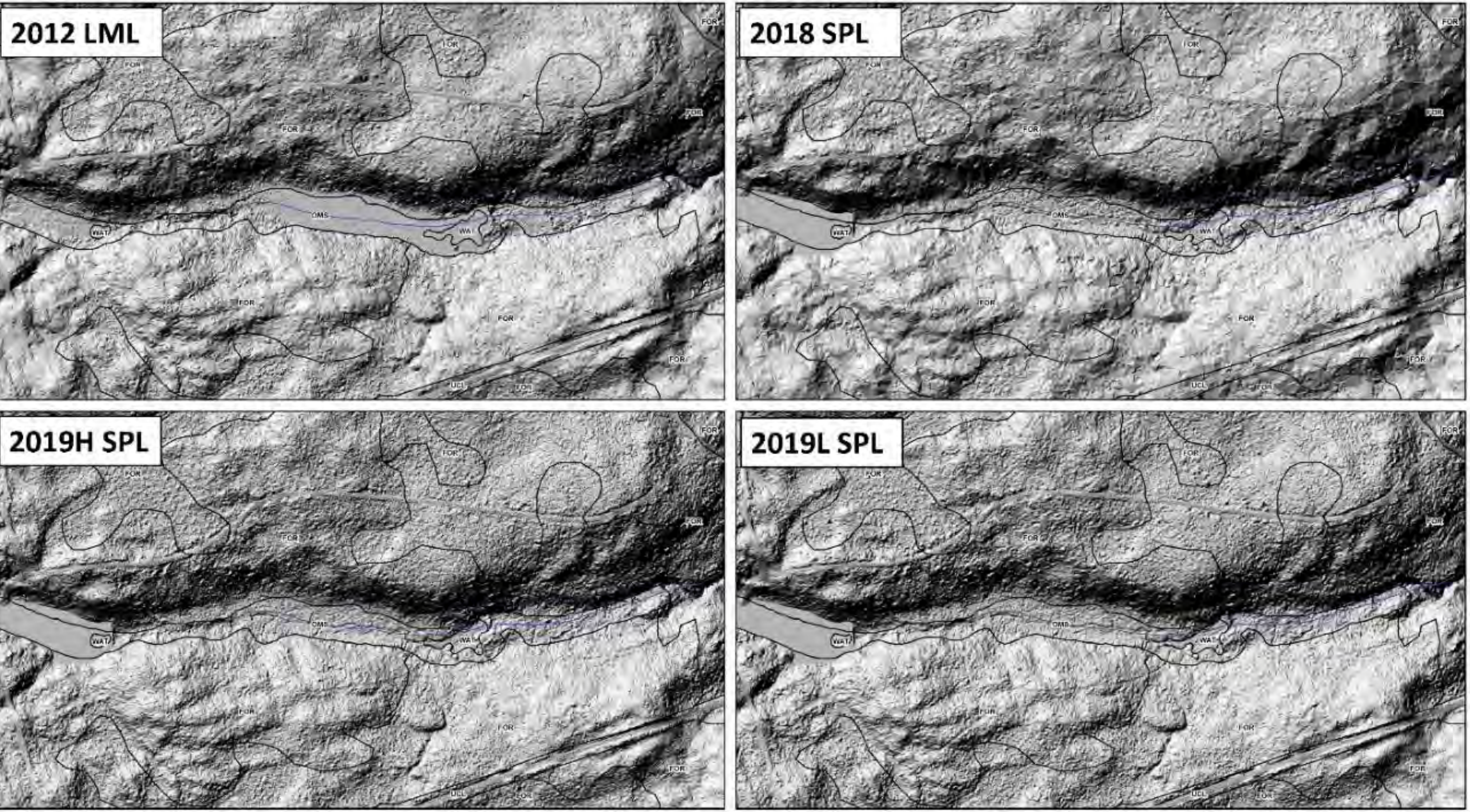
2012 - 2019H

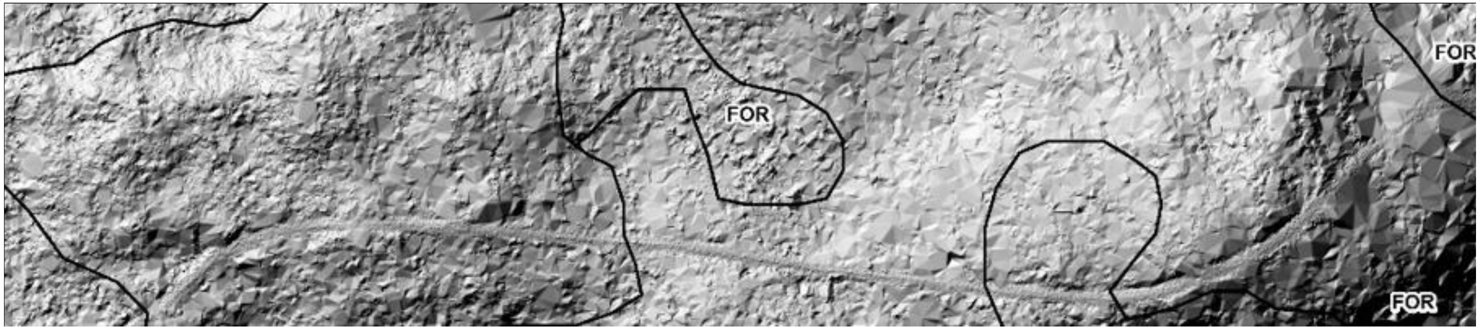
2012 - 2019L

1 m DEMs
Red = SPL overestimates
Black = SPL underestimates

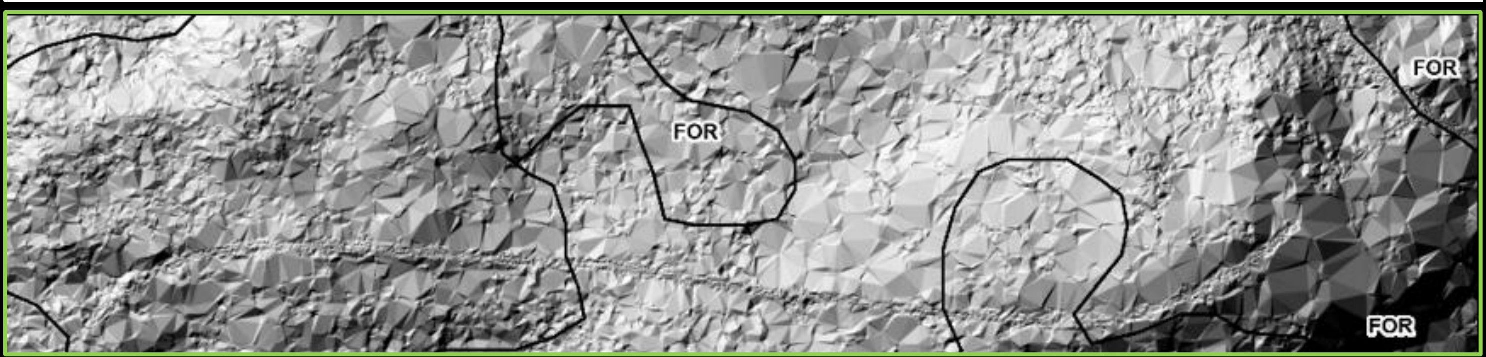
Percentage of pixels within ± 30 cm: 96%
Percentage of pixels within ± 50 cm: 99%

Metric	2018	2019H	2019L
MD (cm)	-7.44	0.80	0.74
RMSD (cm)	18.07	13.37	13.27

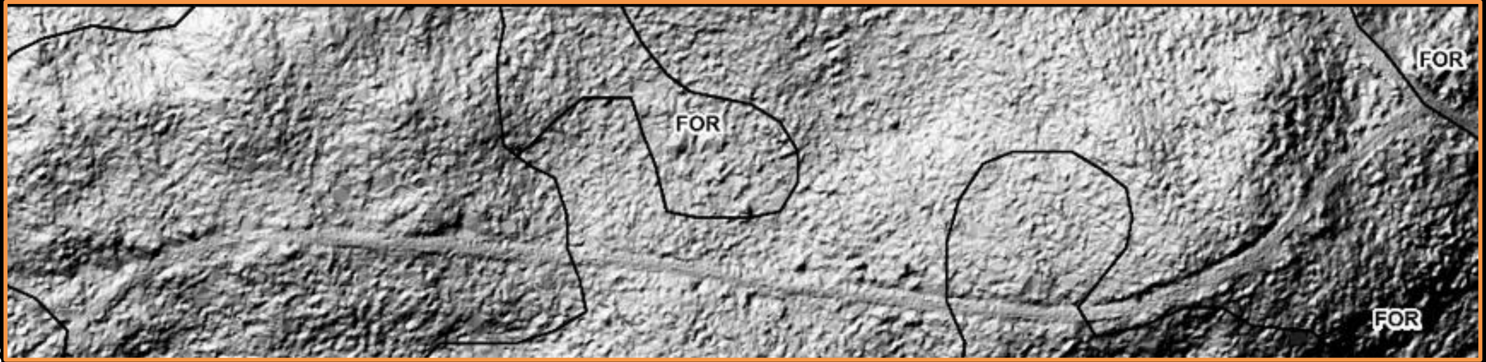

2012 LML
2018 SPL
2019H SPL
2019L SPL



2012
LML

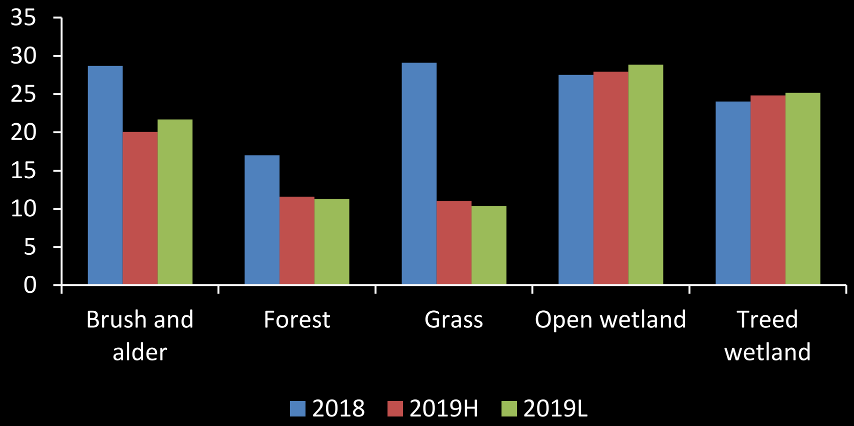


2018
SPL
Leaf-on

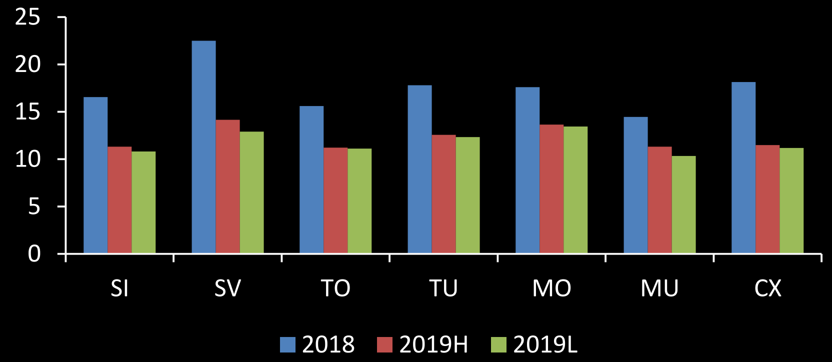


2019
SPL
Leaf-off

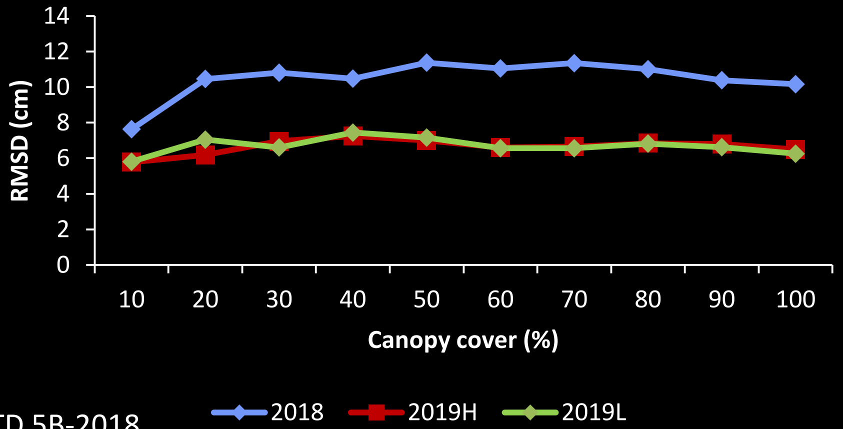
RMSD for DEM differences, by cover type



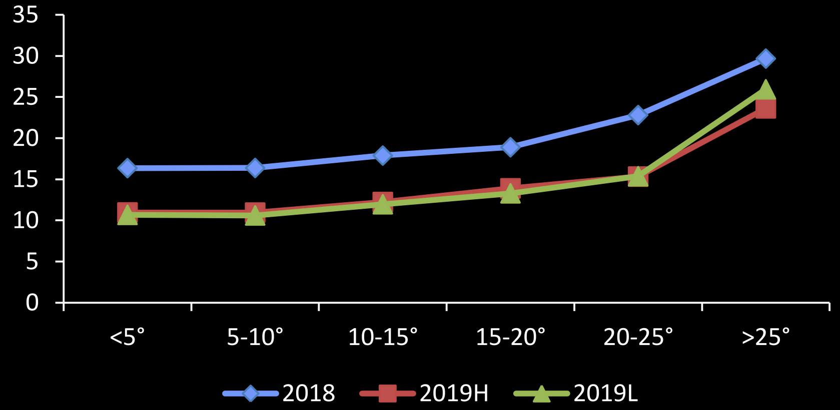
RMSD for DEM differences, by vertical complexity class



RMSD for DEM differences, by canopy cover



RMSD for DEM differences, by slope class

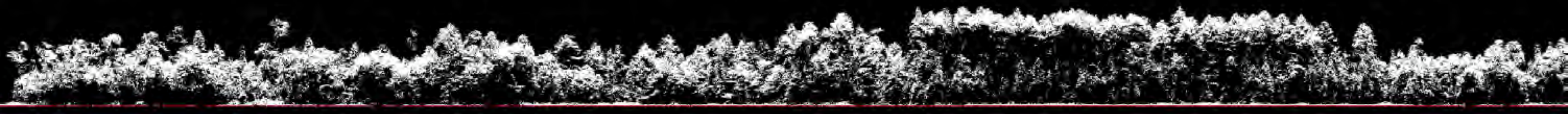


Summary (terrain) 1/3

- Leaf-off SPL data was more accurate than leaf-on SPL data <u>and</u> 2012 LML data for terrain capture under vegetation
- Leaf-off SPL data acquired at lower altitude was more accurate than leaf-off SPL acquired at higher altitude
- Leaf-off data reduced RMSE by 17% (2019H SPL vs 2018 SPL)
- Lower altitude reduced RMSE by only 8% (2019L SPL vs 2019H)

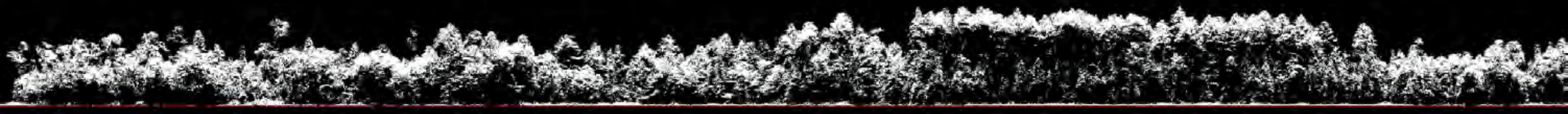
Summary (terrain) 2/3

- No consistent trends between canopy cover and the accuracy of terrain capture
- Vegetation density, composition, and configuration influences accuracy of terrain capture
- Differences in lidar characteristic do result in differences in derived DEMs



Summary (terrain) 3/3

- Under vegetation cover, leaf-on SPL data is less accurate and less precise than either leaf-off SPL or LML, but accuracy is within requirements for CQL1 products



White, J.C., Woods, M., Krahn, T., Papasodoro, C., Bélanger, D., Onafrychuk, C., Sinclair, I. 2021. Evaluating the capacity of single photon lidar for terrain characterization under a range of forest conditions. *Remote Sensing of Environment*, 252, 112169. DOI: 10.1016/j.rse.2020.112169

https://doi.org/10.1016/j.rse.2020.112169

Open Access

Remote Sensing of Environment 252 (2021) 112169

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Evaluating the capacity of single photon lidar for terrain characterization under a range of forest conditions

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ARTICLE INFO

Keywords:
Forestry
Elevation
SPL
ALS
Lidar
Forest inventory

ABSTRACT

Accurate digital elevation models are key data products used to inform forest management. Light detection and ranging (lidar) technologies have emerged as a useful tool for acquiring detailed terrain information, although the accuracy of this data is known to vary with topographic complexity and the density and characteristics of overlying vegetation. Single Photon Lidar (SPL) provides a high-density point cloud that can be acquired from a much higher altitude than discrete return, small-footprint lidar (hereafter, linear-mode lidar or LML), providing efficiencies and potential cost savings for operational mapping programs. Herein, we assess the absolute and relative accuracies of leaf-on and leaf-off SPL data acquired at different altitudes for characterizing terrain under varying vegetation types and densities and compare to results for LML data. Our assessment was forest-focused and primarily point based, using 299 Real-Time Kinematic survey checkpoints to quantify elevation errors (Δh); however, we also investigated and reported accuracy for linear transects, and conducted a wall-to-wall comparison of the SPL-derived 1-m digital elevation models (DEMs) against an LML-derived DEM. Point cloud characteristics for the leaf-on 2018 SPL data were markedly different, with 88% of returns as first returns, compared to 17% for the LML, and 59% and 46% for the leaf-off SPL data acquired at 3800 m and 2000 m, respectively. Of the datasets considered herein, the SPL data acquired under leaf-on conditions in 2018 had the lowest accuracy and precision for characterizing terrain underneath vegetation cover, with an RMSE of 10.97 cm and a 95th quantile of 24.03 cm; however these values are within commonly accepted error limits for elevation products. The leaf-off SPL data were most accurate overall; however, the differences between the leaf-off SPL data acquired at 3800 m versus 2000 m were often minor (< 1 cm on average), with similar patterns in Δh between the two datasets ($r = 0.8$). In terms of the relative performance of the lidar datasets examined, results from the analyses of linear transects were similar to those of the checkpoints, but highlighted the variability in elevation accuracy within similar cover types. Wall-to-wall comparisons of the SPL-derived DEMs to the 2012 LML DEM also corroborated the results of the checkpoint assessment, with the 2018 SPL leaf-on DEM having the largest differences (mean difference = 7.44 cm; RMSD = 18.07 cm). Differences between DEMs did not trend consistently with increasing canopy cover or with the percentage of returns that were within ±15 cm of the ground surface. We found that it was not only the density of the vegetation, but also the composition and configuration of both the overstory and understory vegetation that influenced the accuracy with which the lidar characterized the terrain surface. Overall, our results indicated that leaf-on SPL is capable of capturing terrain information under a wide variety of forest and vegetation conditions, albeit at a lower accuracy than what is possible with leaf-on LML or leaf-off SPL, but at a level of accuracy that is within acceptable limits for most forest applications.

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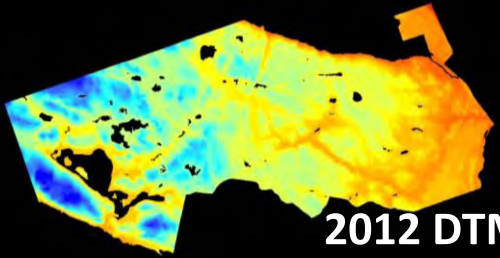
https://doi.org/10.1016/j.rse.2020.112169
Received 20 July 2020; Received in revised form 17 October 2020; Accepted 27 October 2020
Available online 3 November 2020

Key project takeaways:

- SPL area-based attribute predictions are on par with those attained using LML data in the same forest types, and those using SPL data in different forest environment;
- Leaf-on SPL data acquired at 3800 m agl provides terrain accuracies that are within the accuracy requirements for vegetated cover;
- This project enabled novel insights that are of both scientific and operational value;
- Collaborations and partnerships were critical for success;
- Open and transparent science and data are key to innovation in the forest sector…



2012 DTM

2012 CHM

2013 Vexcel Ultracam

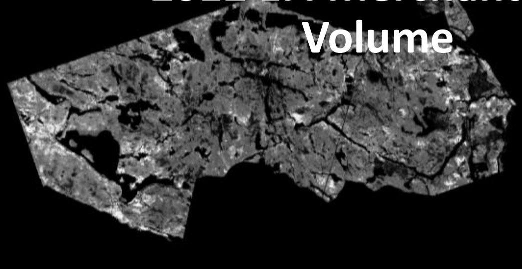
Petawawa Research Forest: Remote Sensing Supersite

https://opendata.nfis.org/mapserver/PRF.html

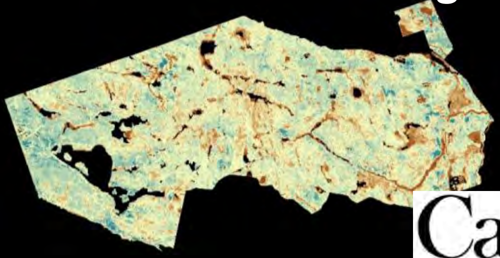
SPL: https://opendata.nfis.org/downloads/petawawa/Raster/LiDAR_2018/PRF_LiDAR2018_LAS.zip

2007 Forest Inventory

2012 EFI Merchantable Volume



2012 EFI Mean Height



Canada

Thank you!

Thanks to the Forestry Future's Trust and all of our partners, collaborators, and contributors.

Joanne White, Research Scientist

Canadian Forest Service

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@Joanne_C_White #CFSEFI