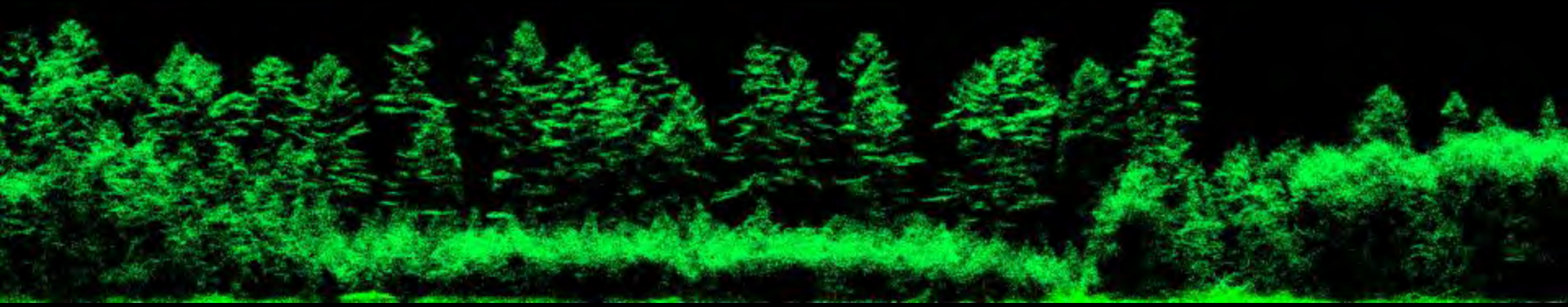
Exploring the innovation potential of single photon lidar for large-area forest inventories



Operational Lidar Inventory Meeting

April 6, 2022

Dr. Joanne White

Research Scientist

Canadian Forest Service

Murray Woods

Retired, OMNRF

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

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

FORESTRY FUTURES TRUST ONTARIO

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

Canadian Institute of Forestry
Institut Forestier du Canada

Ontario

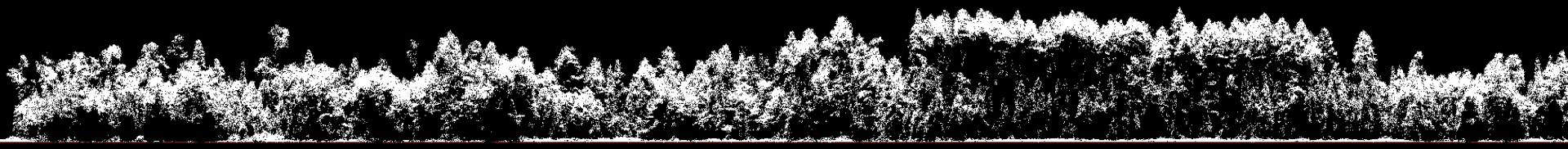
FPInnovations

CIF-IFC SEEK

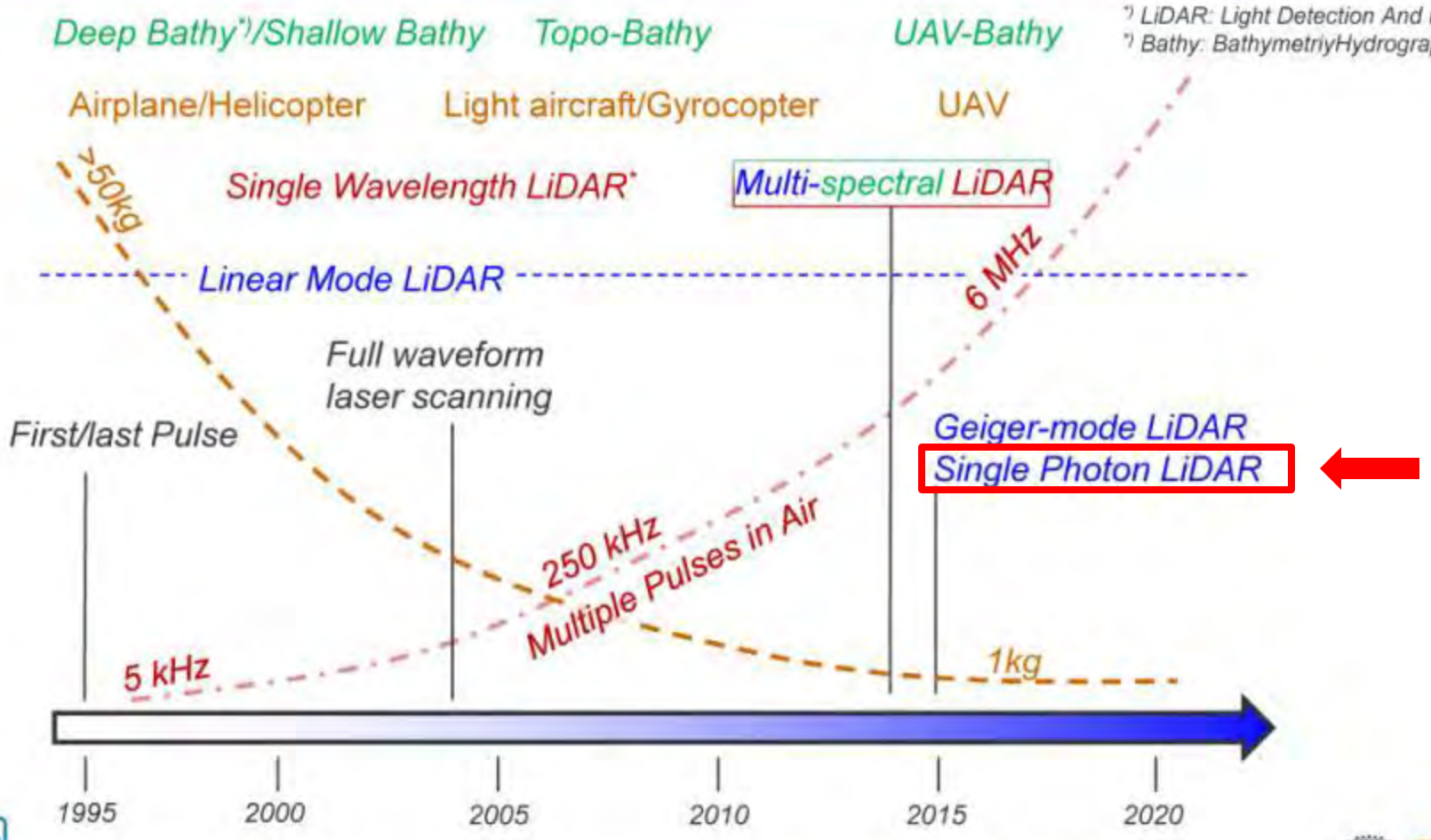
Project objectives

Quantify the performance of single photon lidar (SPL) for:

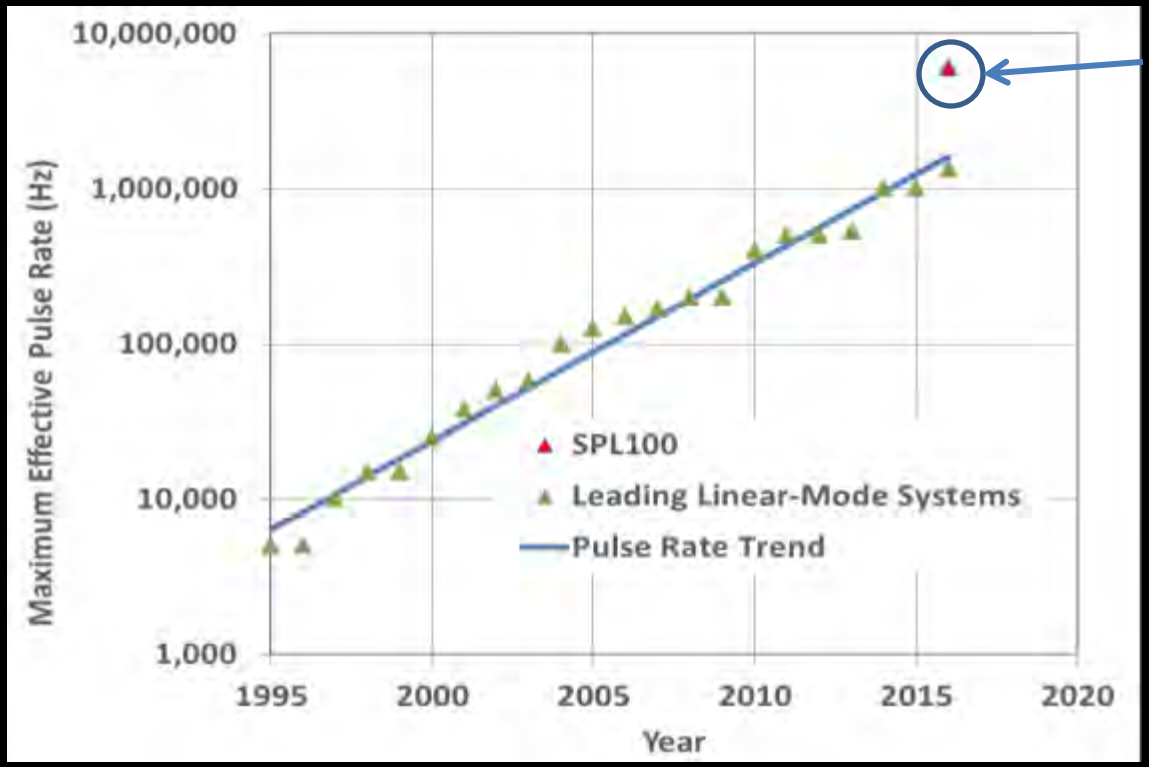
1. characterizing terrain surface under a range of forest conditions and types
2. estimating forest inventory attributes in an area-based approach



Timeline Airborne Laser Scanning

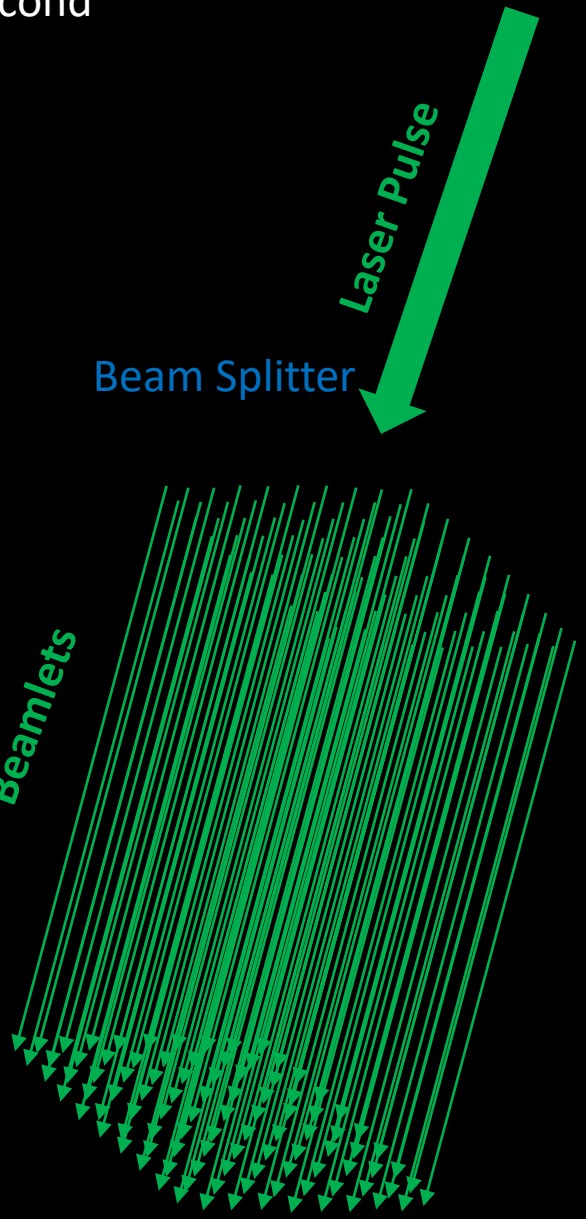


Source: G. Mandlburger



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



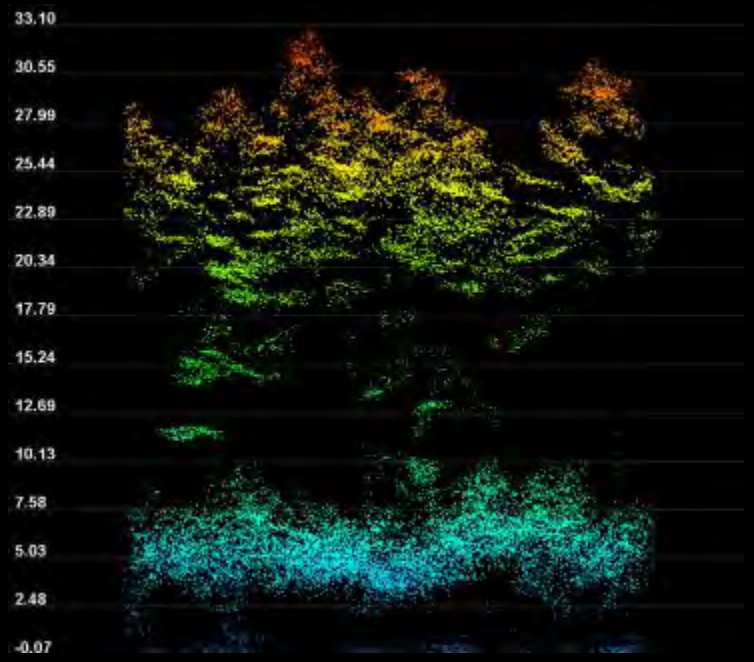
High energy

LML versus SPL

Low 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)



High energy

Low energy

LML versus SPL

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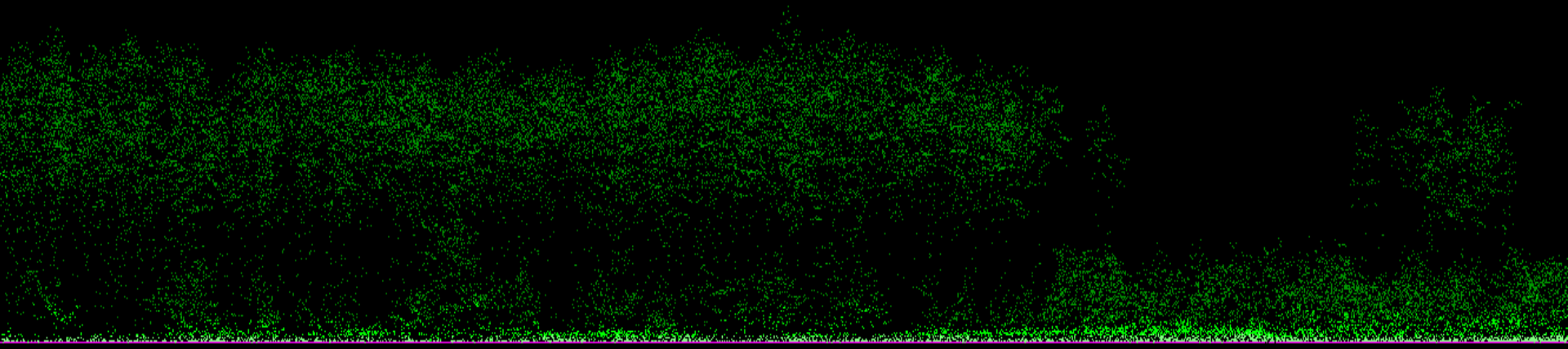
- NIR wavelength (e.g. 1064 nm)
- Acquisition = low and slow
- Multiple returns for a single pulse
- Many photons to register a return = Multi-Photon Lidar (MPL)

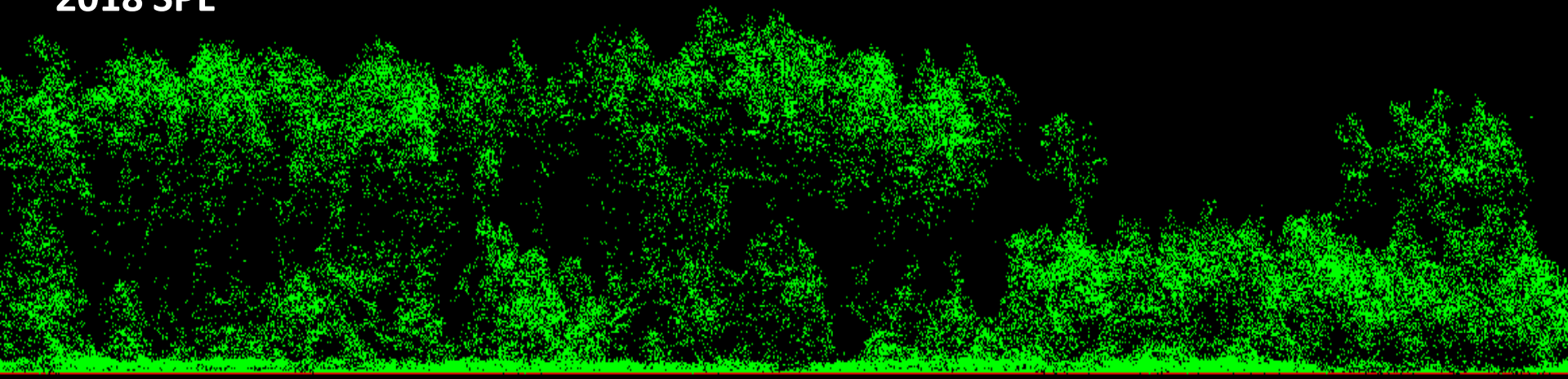
SPL (Single Photon Lidar)

- 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

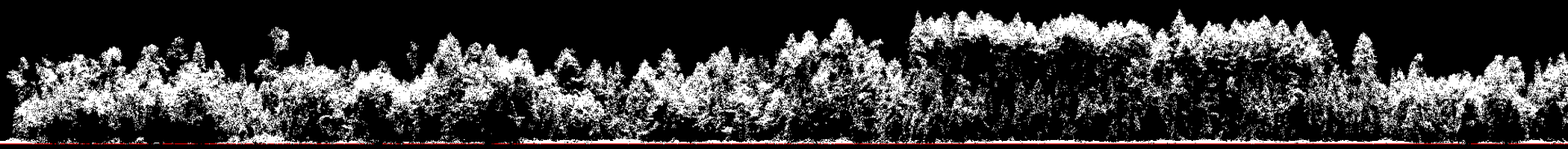


2018 SPL



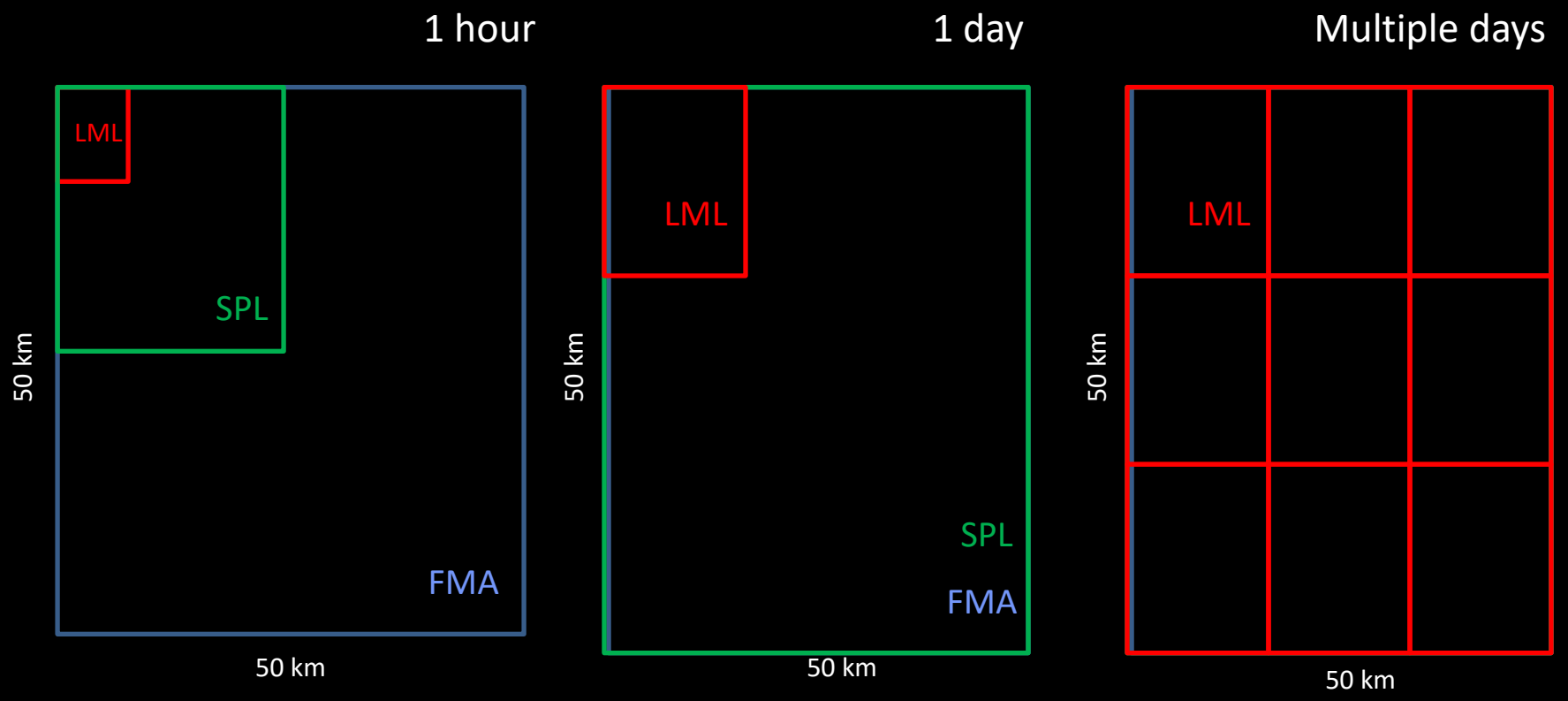
Single Photon Lidar: Acquisition capacity

- Wästlund et al. 2018 (Sweden):
  - *SPL covered 590 km^2/hour, LML covered 50 km^2/hour*
- Mandlburger 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*



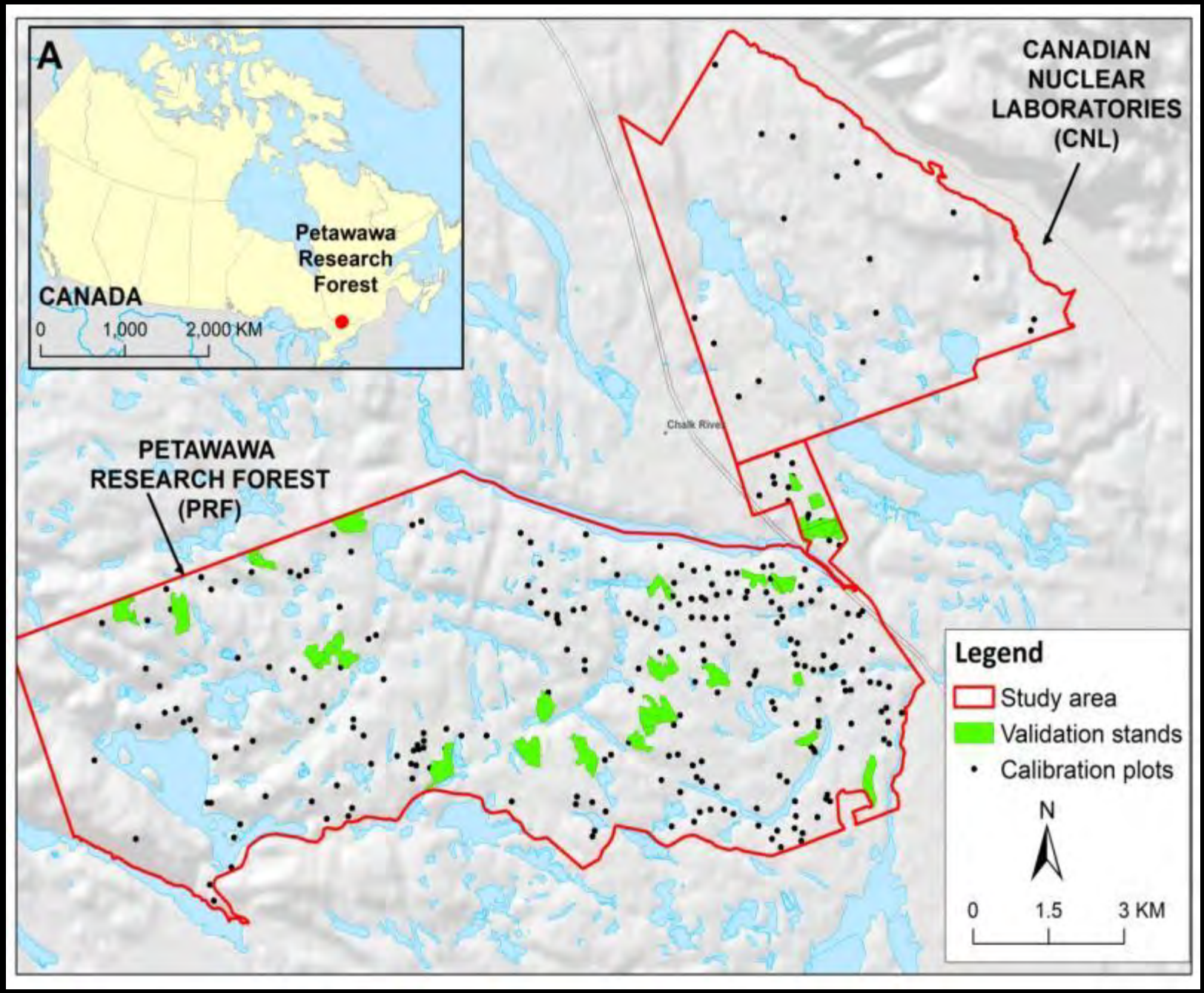
Single Photon Lidar: Acquisition capacity

Enables lidar acquisitions over very large areas with consistent parameters



Single Photon Lidar: Acquisition challenge

Area of the undertaking (AOU)
~38.5 million ha


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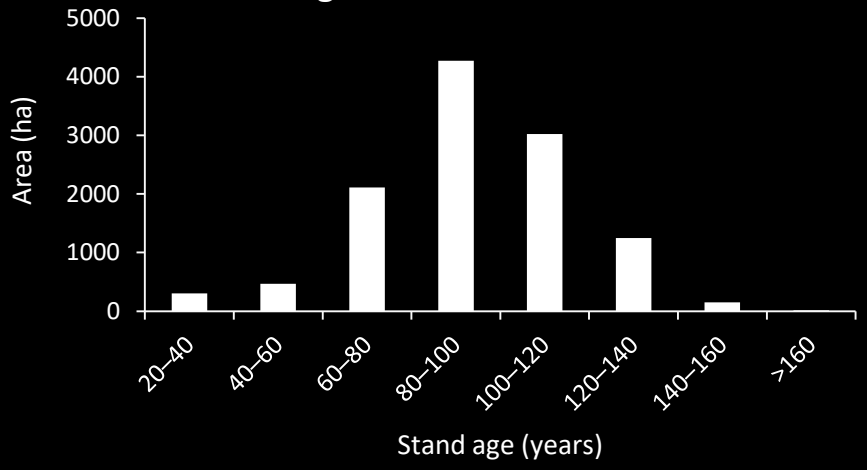
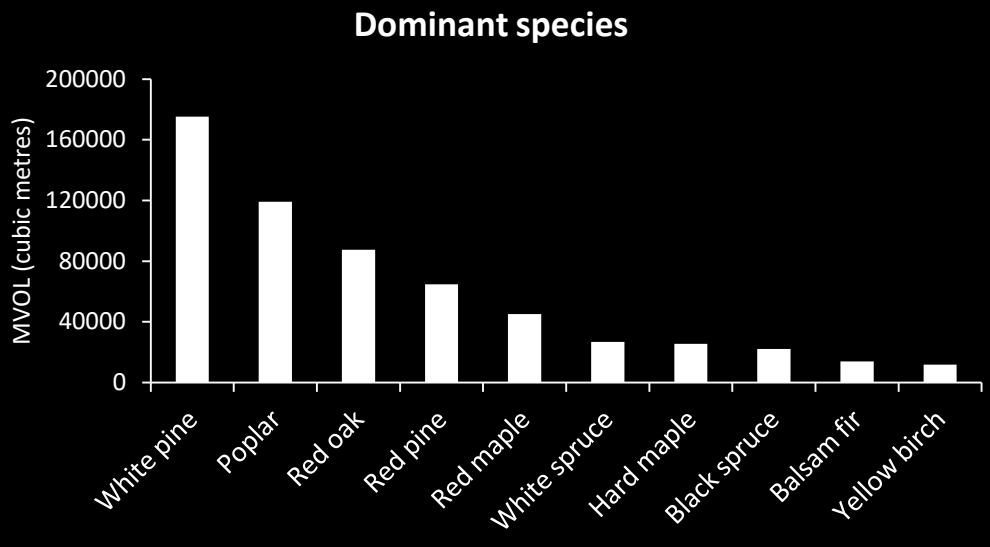
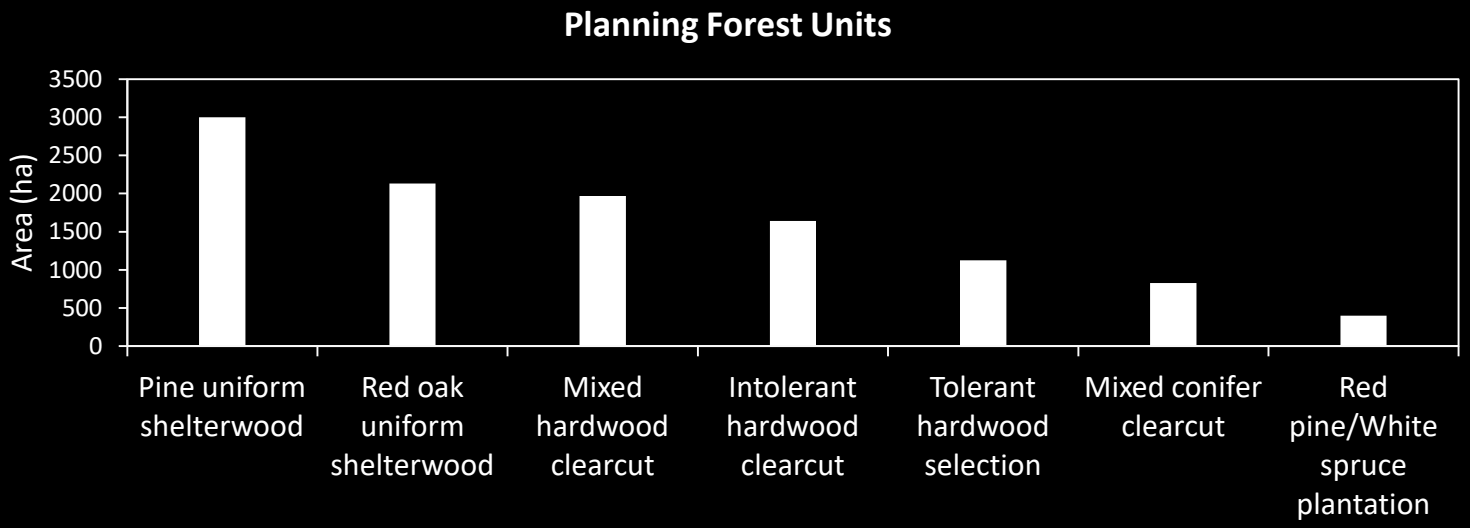
RESEARCH FOREST
(PRF)
Legend
Study area
Validation stands
Calibration plots
N
0
1.5
3 KM

Study area







Source: L.Cobb, CWFC

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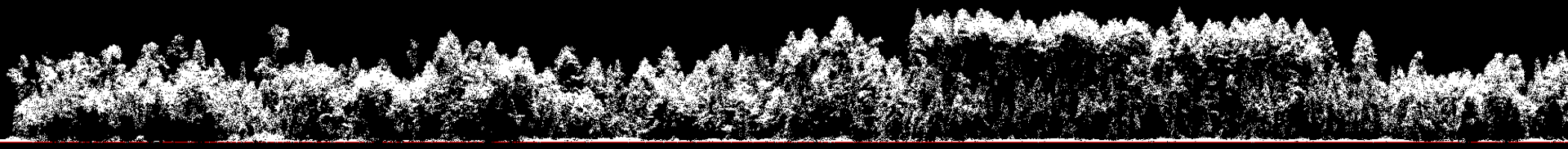


Evaluating the capacity of single photon lidar for terrain characterization under vegetation canopy

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

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

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

[3]Provincial Mapping Unit, Mapping and Information Resources Branch, Ontario Ministry of Natural Resources and Forestry

[4]Canada Centre for Mapping and Earth Observation

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

Research objectives (terrain)

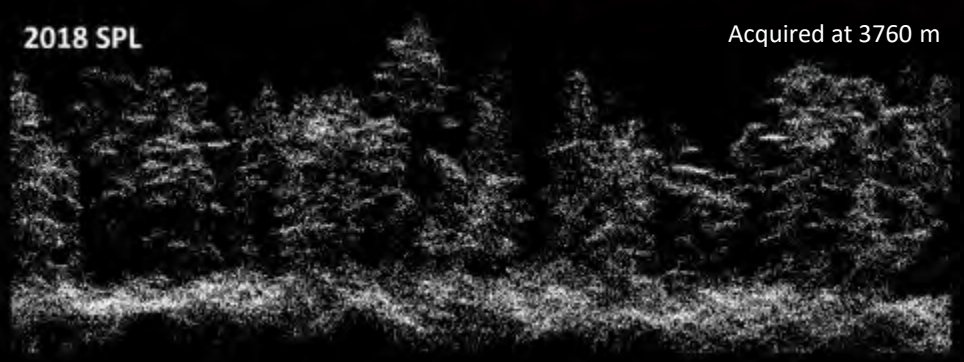
1. Quantify the vertical accuracy and precision of SPL data (leaf-on and leaf-off) for characterizing terrain surface elevations under a range of forest conditions and acquisition altitudes (3760 m versus 2000 m) — checkpoints

2. Evaluate derived DEMs — wall-to-wall, spatially explicit

Lidar data

Leaf-on

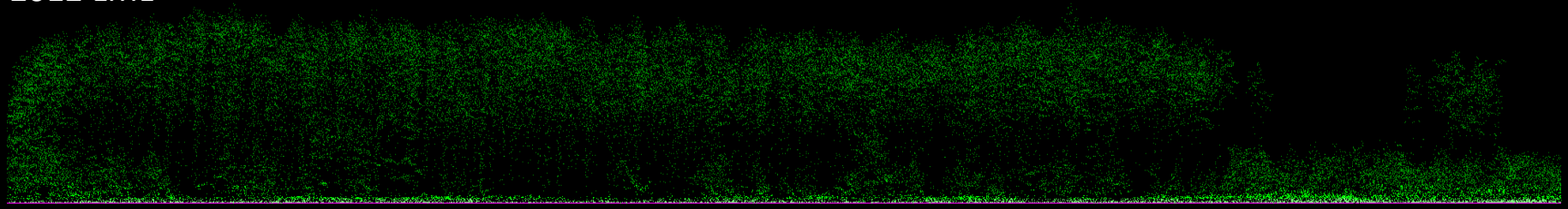
Leaf-off



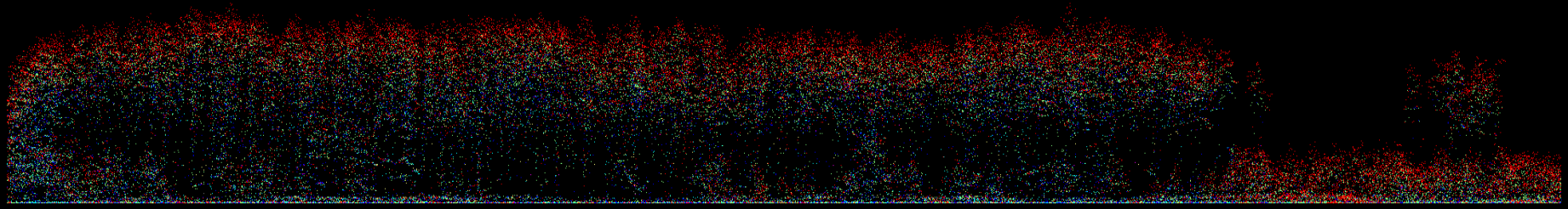
Lidar data

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

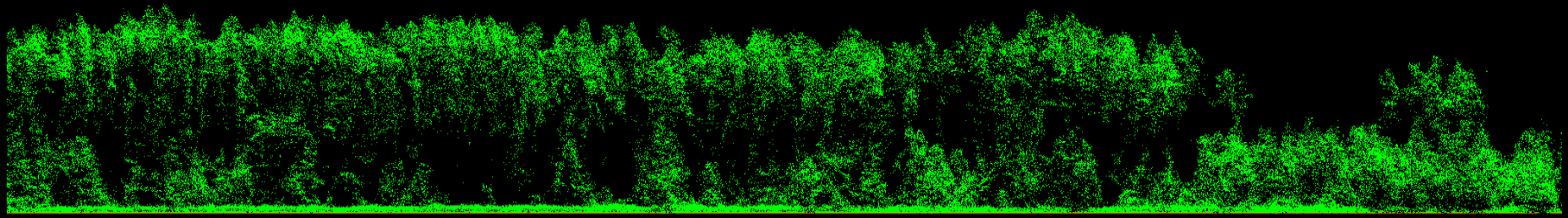
2012 LML



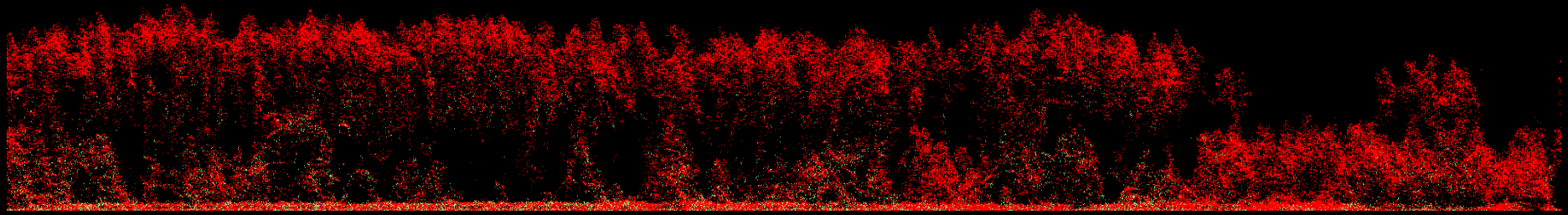
2012 LML by return



2018 SPL



2018 SPL by return



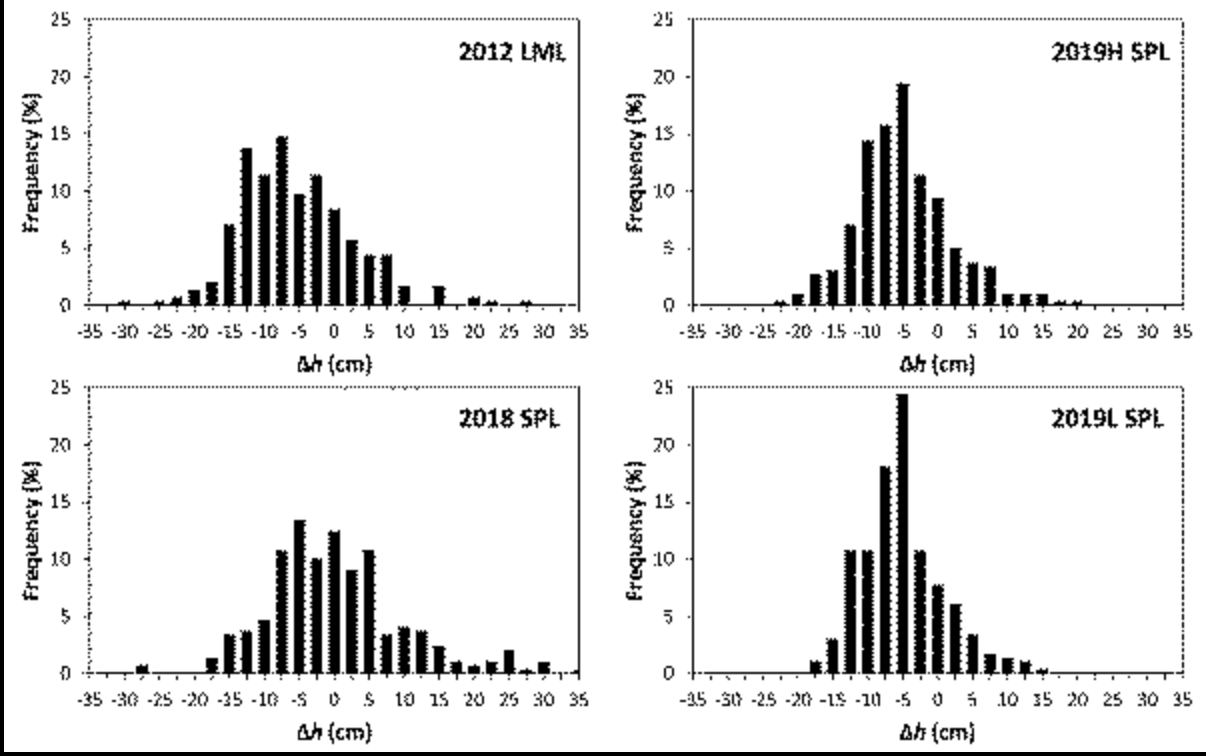
Reference data for terrain evaluation

- 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

Results (checkpoints)

(Lidar z – Reference z)



Results (checkpoints)

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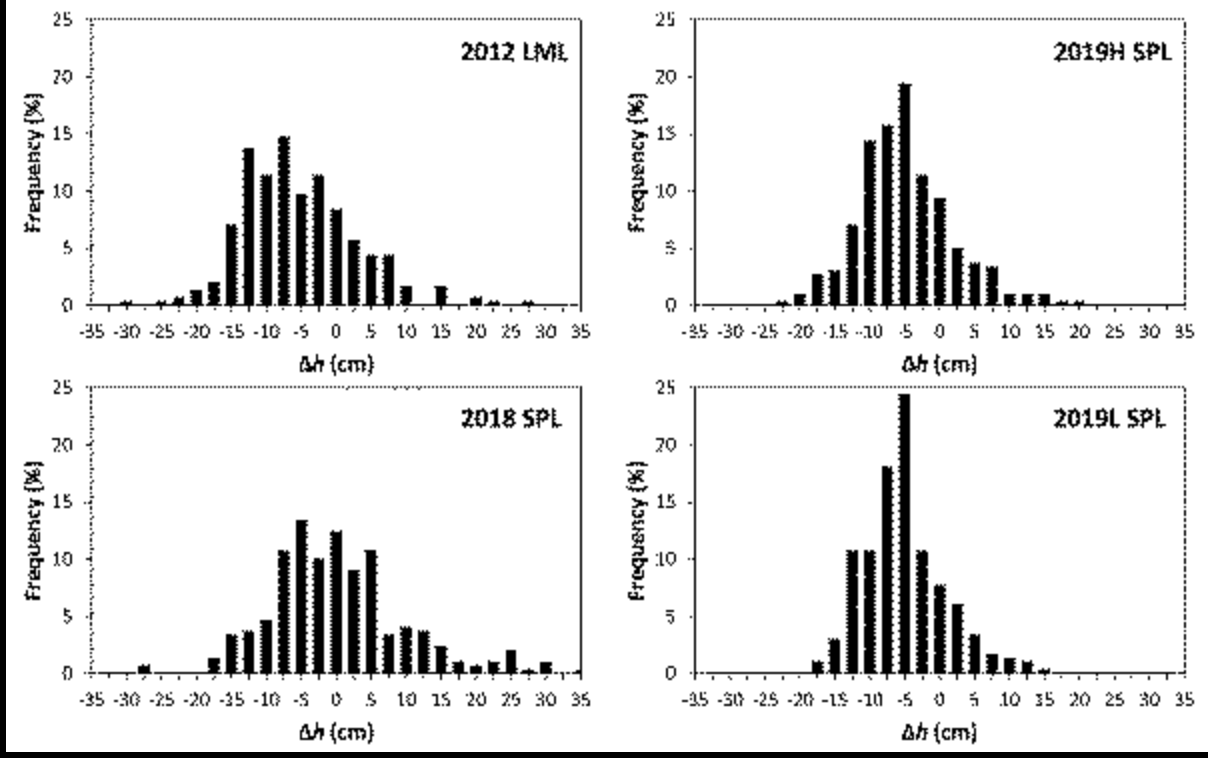
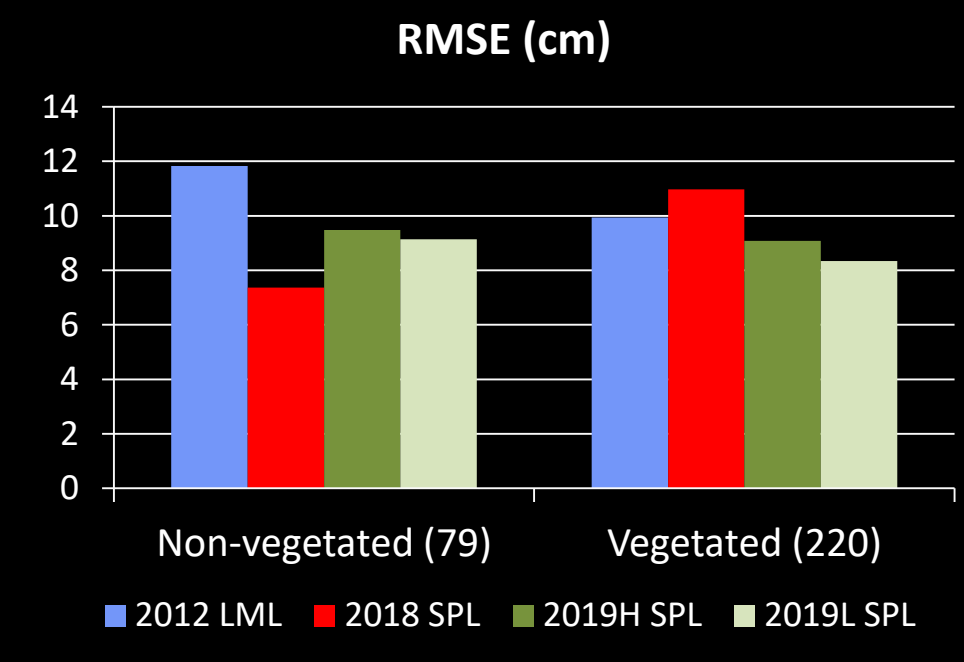
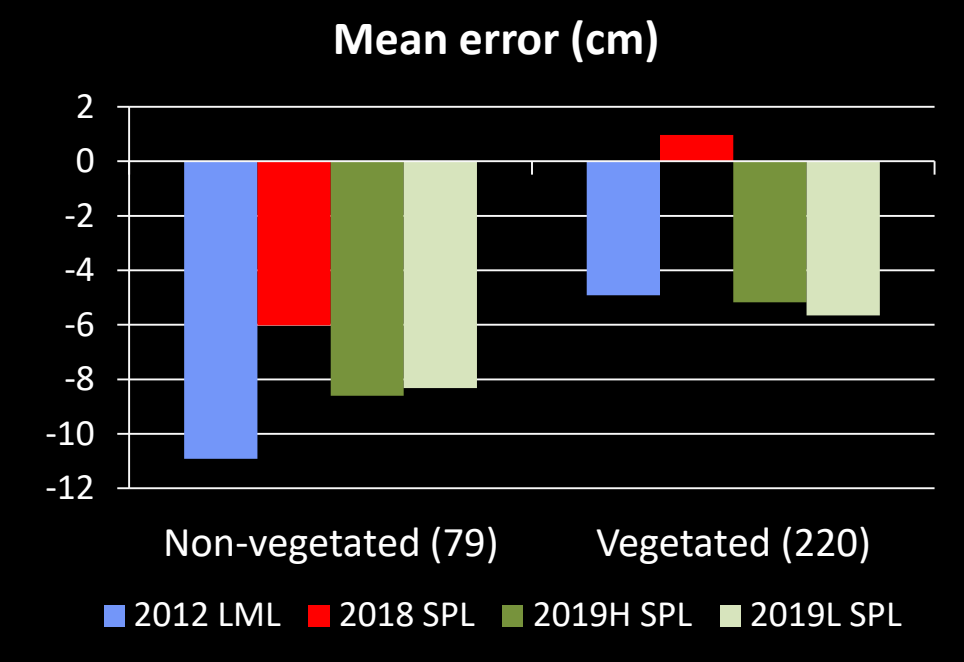
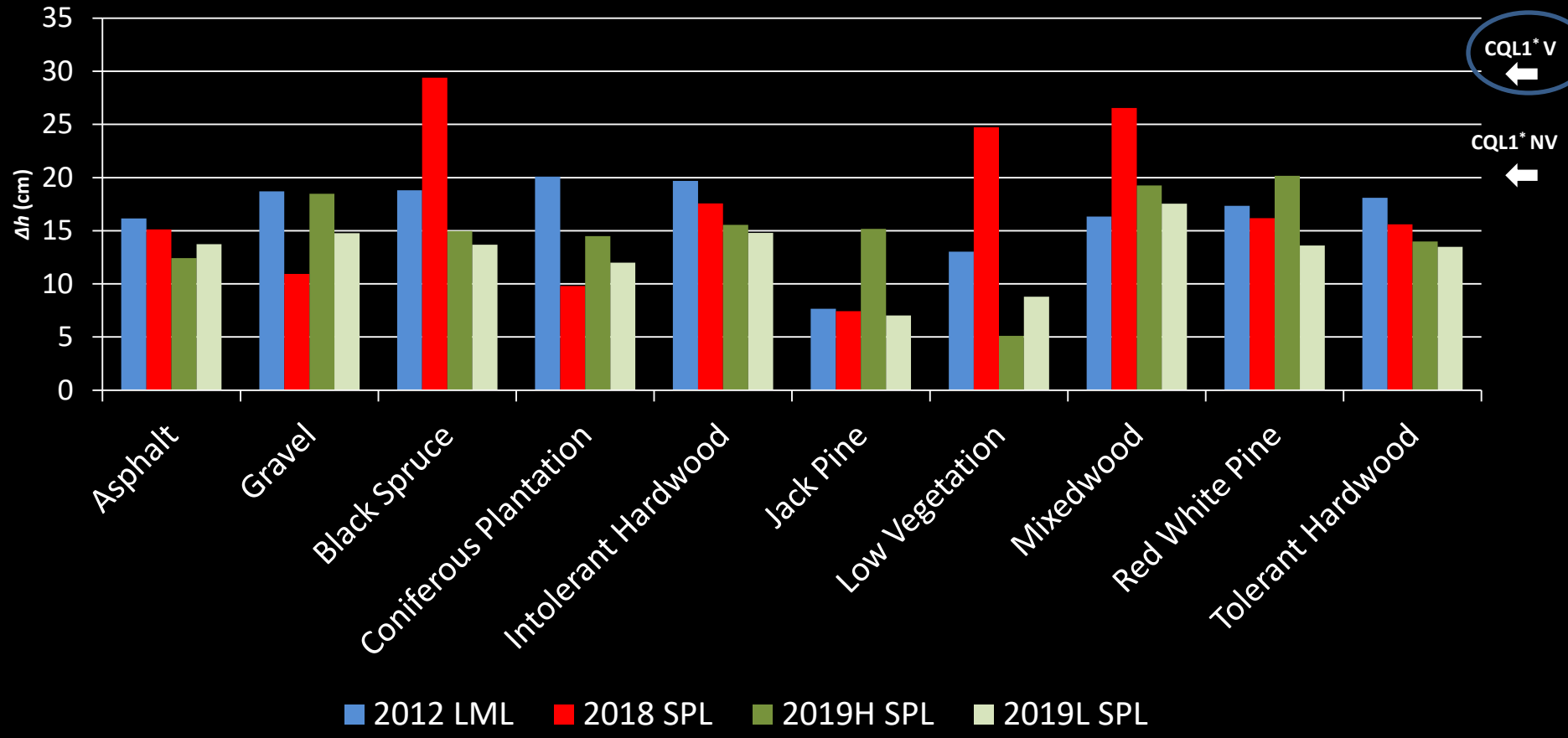






95th Percentile (cm) Δ*h*

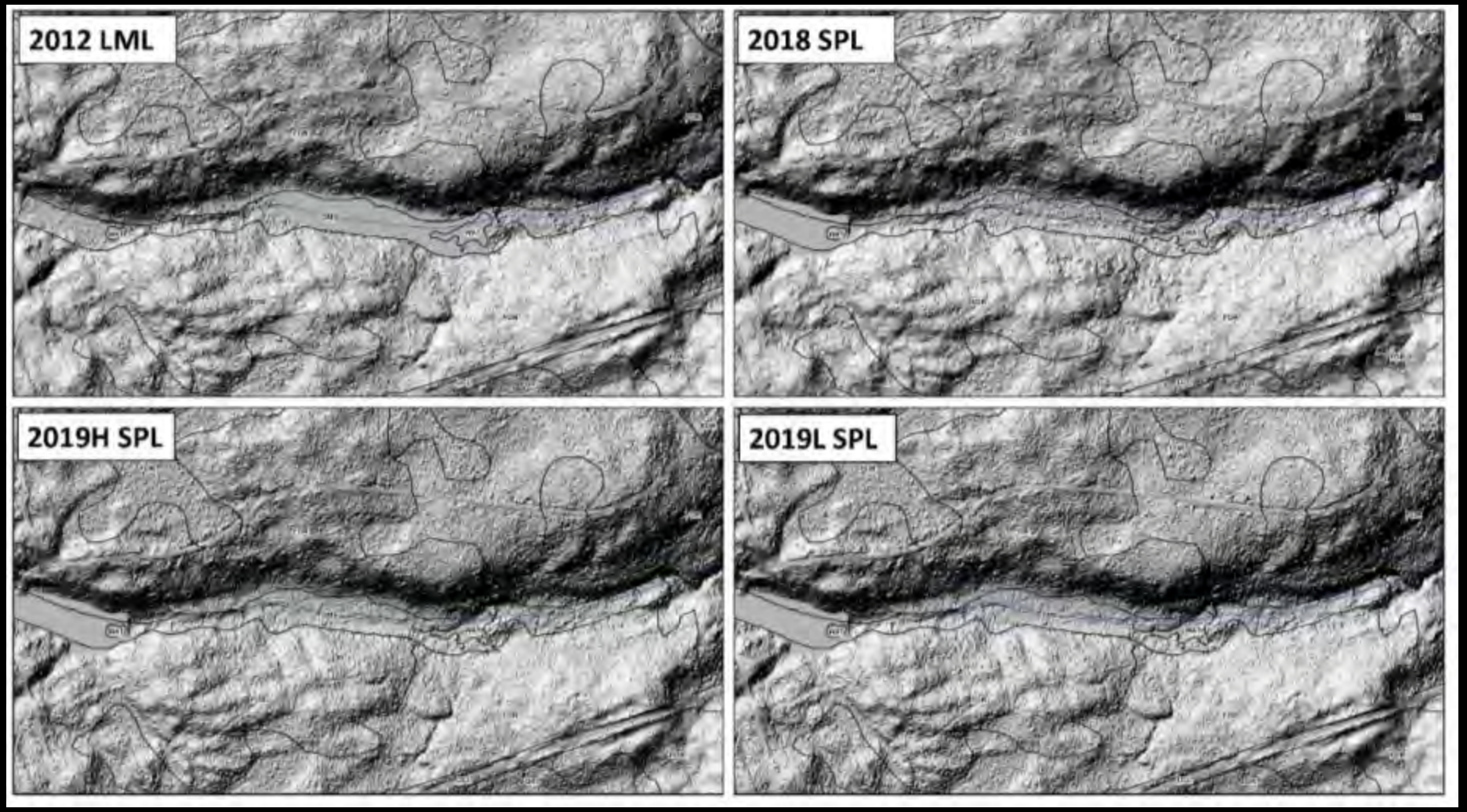


Δh = (Lidar z – Reference z)

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

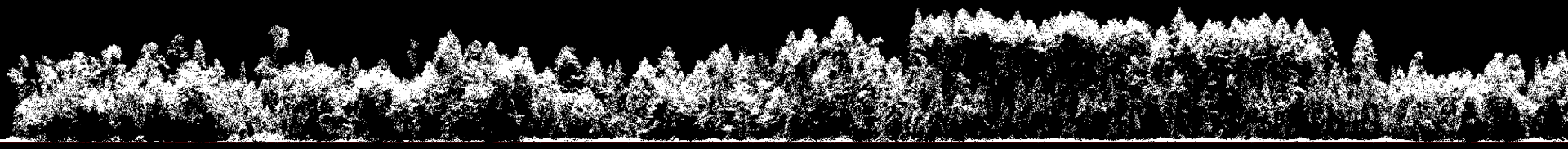
Results (wall-to-wall DEM comparison)

$z_{SPL} - z_{2012}$	2018	2019H	2019L
MD (cm)	7.44	-0.80	-0.74
RMSD (cm)	18.07	13.37	13.27



Summary (terrain)

- Leaf-off SPL data was more accurate than leaf-on SPL data and 2012 LML data for terrain capture under vegetation



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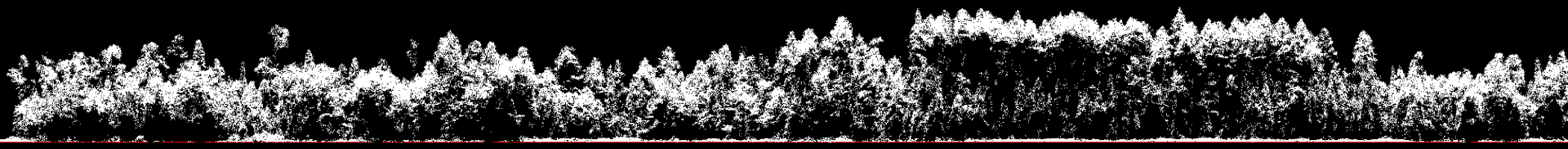
- Leaf-off SPL data acquired at lower altitude was more accurate than leaf-off SPL acquired at higher altitude



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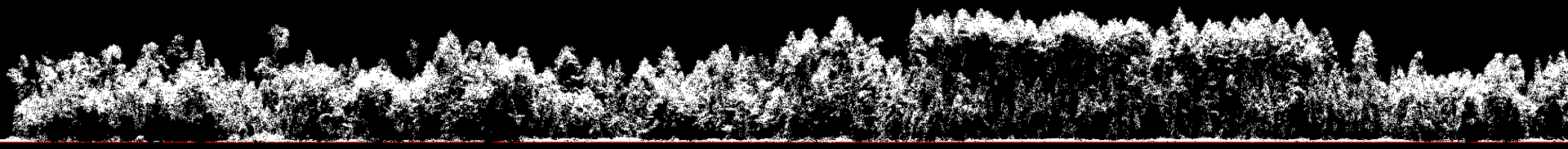

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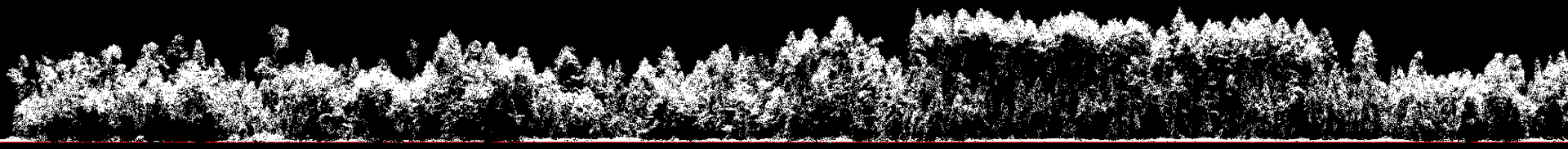
- Lower altitude reduced RMSE by only 8% (2019L SPL vs 2019H)



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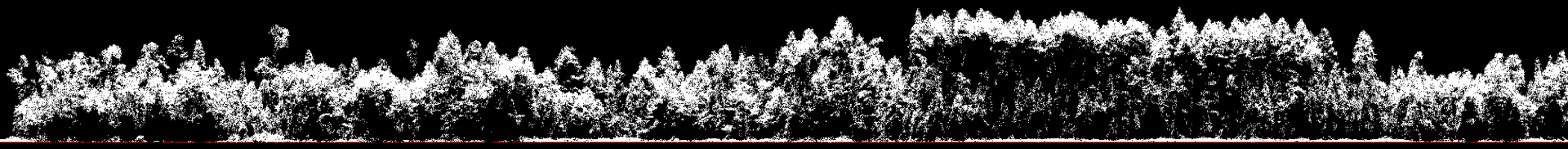
- Leaf-off data reduced RMSE by 17% (2019H SPL vs 2018 SPL)
- Lower altitude reduced RMSE by only 8% (2019L SPL vs 2019H)
- Accuracy for all acquisitions was within requirements for CQL1 products (vegetated)



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

Open Access

Remote Sensing of Environment

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

J.C. White, M. Woods, T. Krahn, C. Papasodoro, D. Bélanger, C. Onafrychuk, I. Sinclair

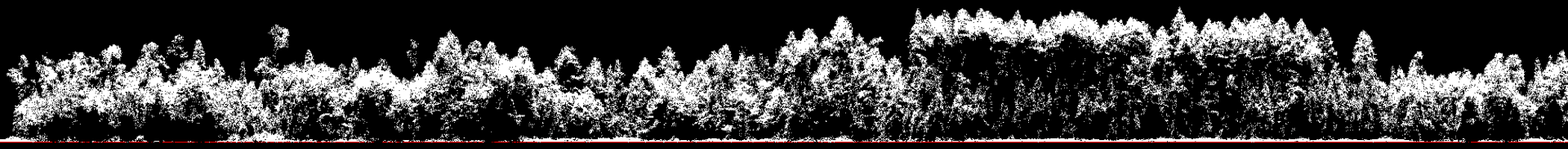
ARTICLE INFO

ABSTRACT

Project objectives

Quantify the performance of single photon lidar (SPL) for:

1. characterizing terrain surface under a range of forest conditions and types
2. estimating forest inventory attributes in an area-based approach



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.

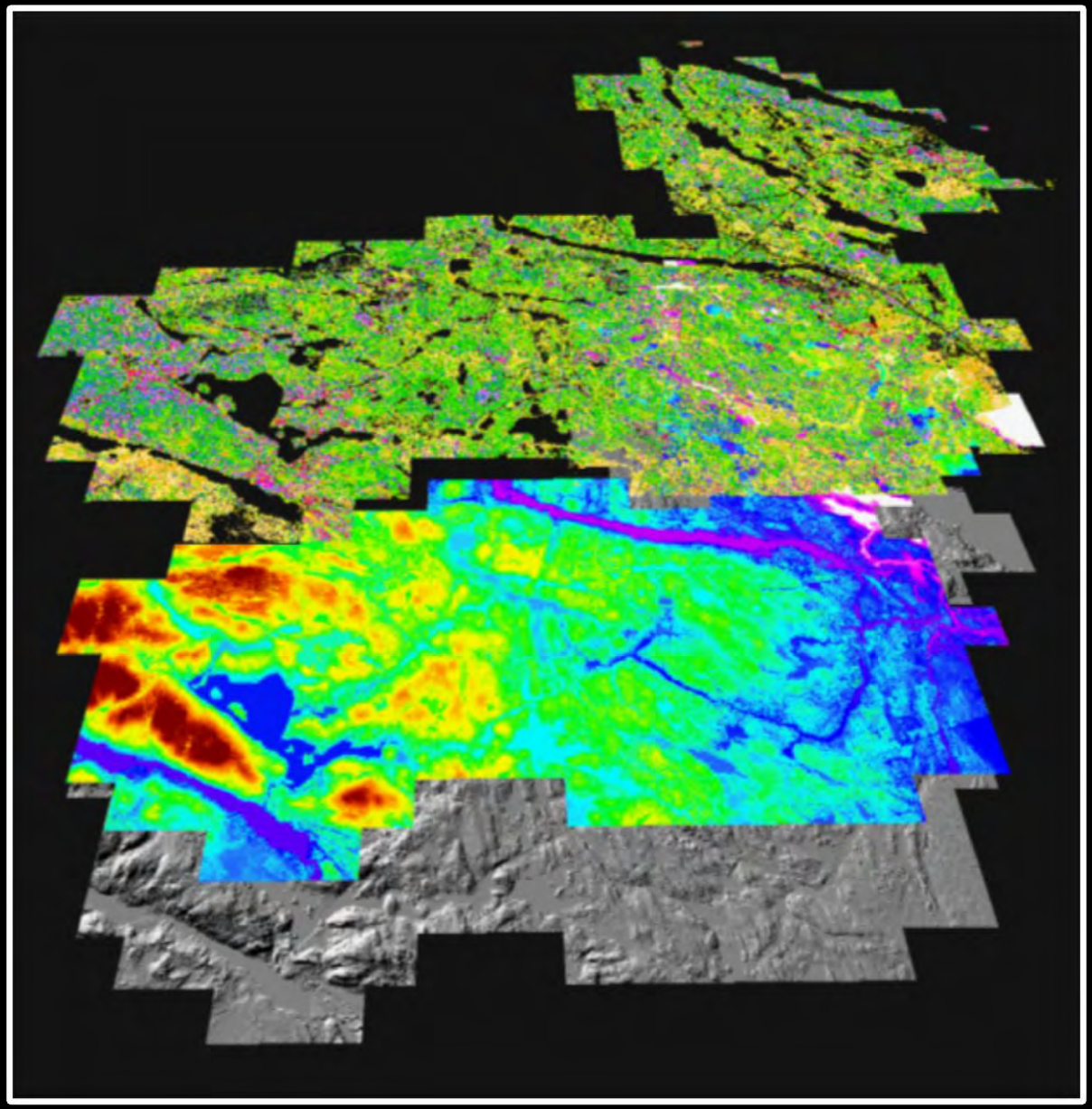
[3]Retired - Natural Resources Information Section, Science and Research Branch, Ontario Ministry of Natural Resources and Forestry

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 accuracy of inventory estimates varied by forest type using independent intensively sampled, stand-level validation data.

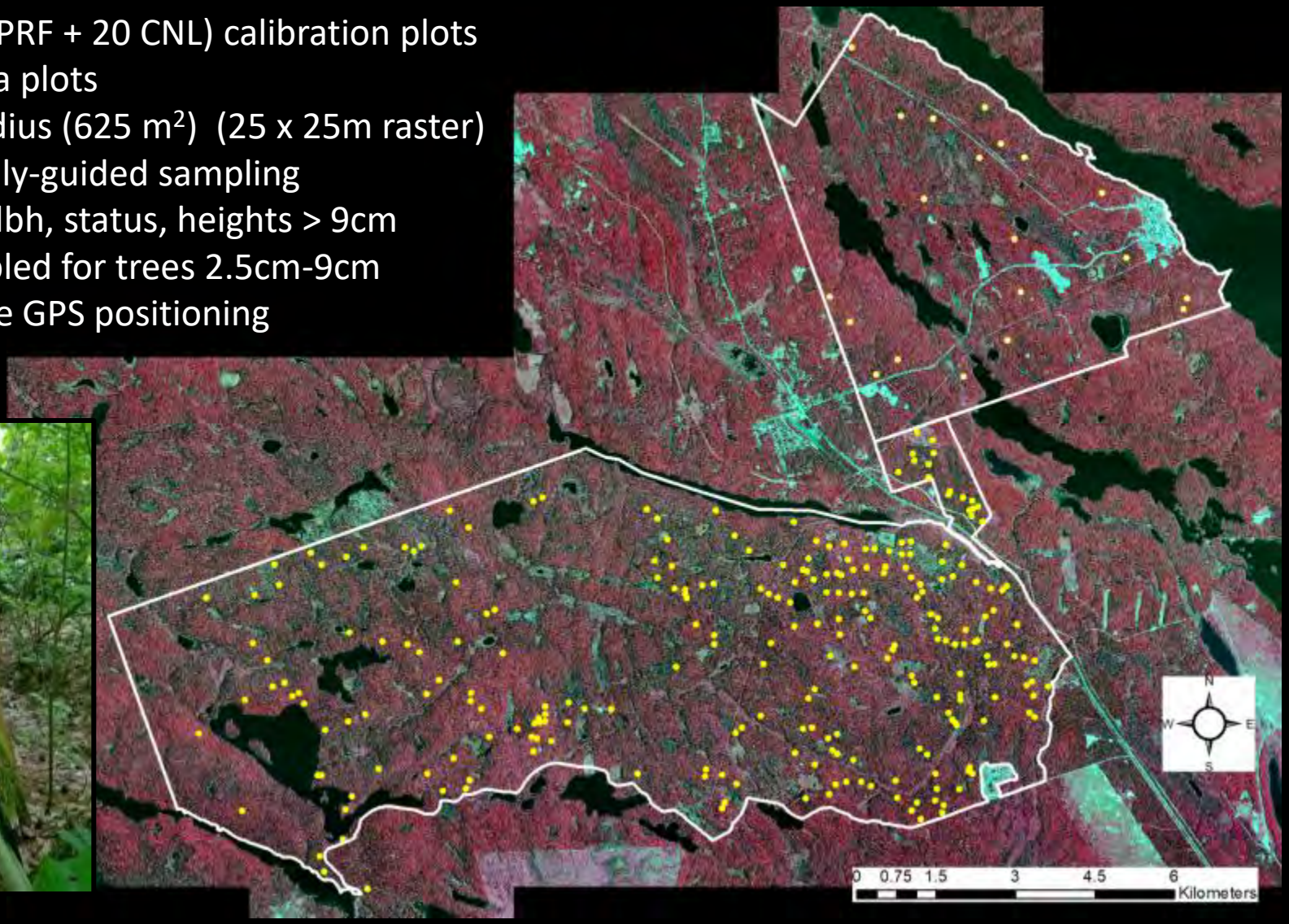
SPL data

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



Calibration data

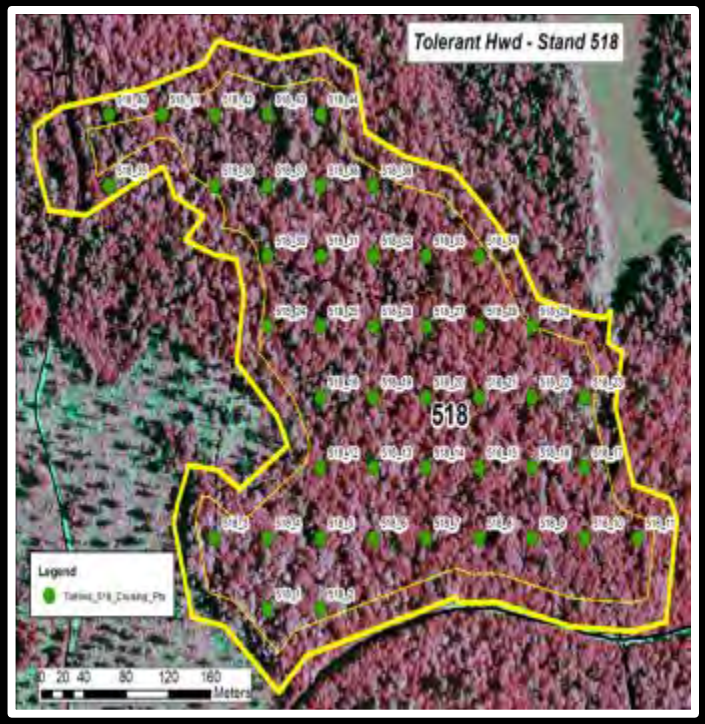
- 269 (249 PRF + 20 CNL) calibration plots
- Fixed-area plots
- 14.1m radius (625 m^2) (25 x 25m raster)
- Structurally-guided sampling
- Species, dbh, status, heights > 9cm
- Sub-sampled for trees 2.5cm-9cm
- Sub-metre GPS positioning

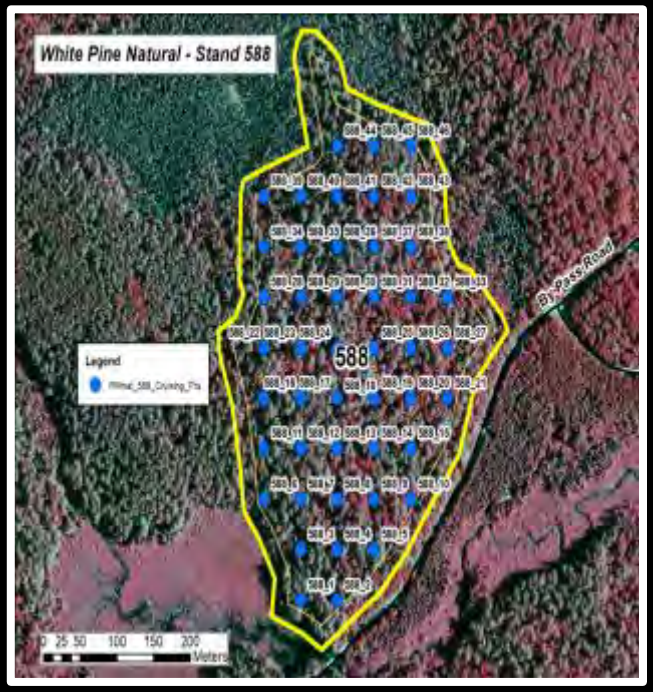


Validation data

- 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

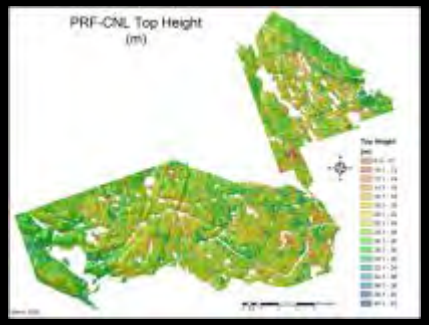
Management size class
- 4 size classes: poles, small, medium, large
- BA, QMD, TVOL_merch, MVOL, Biomass, VBAR, TPH

[1]Used to ensure logical estimates

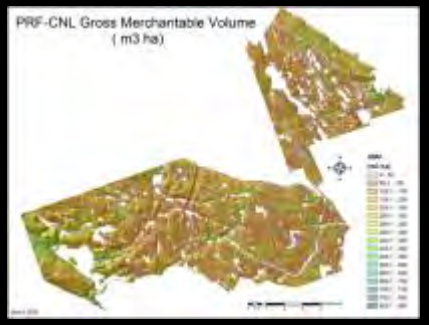
*Derived from other predicted attributes

No forest type information used in modeling

Results


PRF-CNL Top Height
(m)

PRF-CNL Basal Area All
(m2 ha)

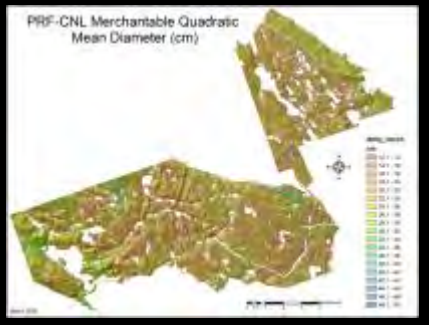

PRF-CNL Gross Merchantable Volume
(m3 ha)

PRF-CNL Total Merchantable Volume
(m3 ha)

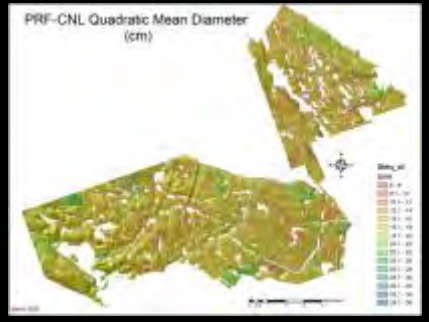
PRF-CNL Codominant/Dominant Height
(m)

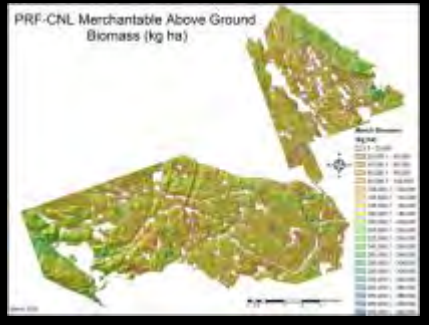
PRF-CNL Basal Area Merchantable
(m2 ha)

PRF-CNL Gross Total Volume
(m3 ha)


PRF-CNL Merchantable Quadratic
Mean Diameter (cm)

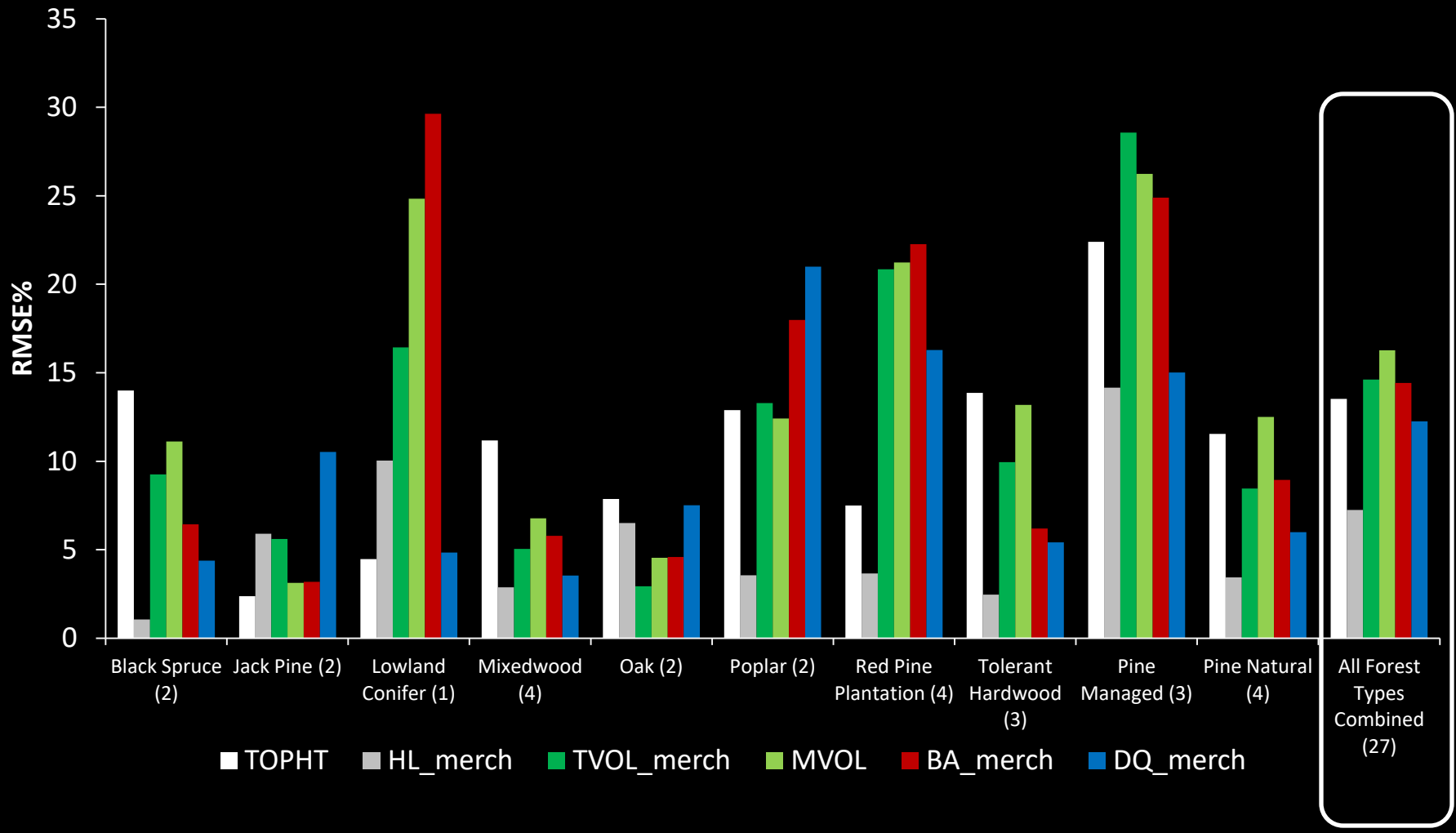
PRF-CNL Lorey Height Merchantable
(m)

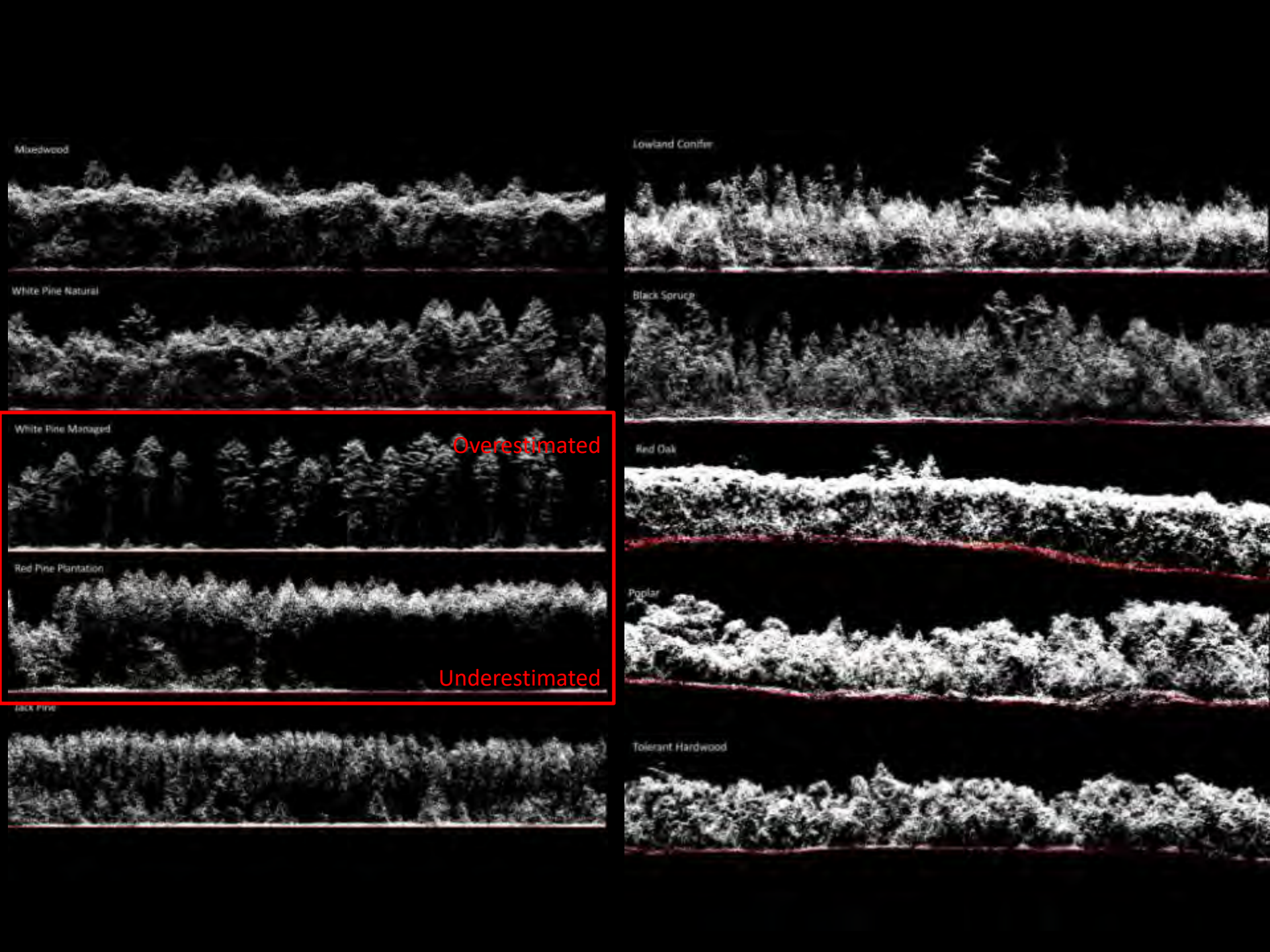

PRF-CNL Quadratic Mean Diameter
(cm)


PRF-CNL Merchantable Above Ground
Biomass (kg ha)

PRF-CNL Density
(stems>9cm ha)

Stand-level validation results




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

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			

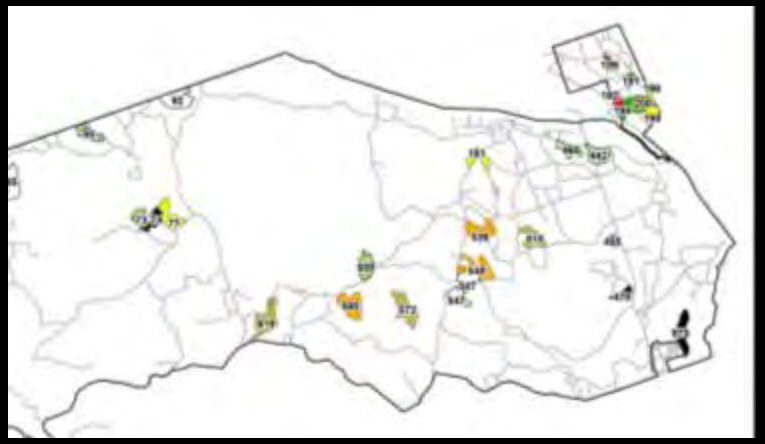
2012 validation stands

2018 Validation:

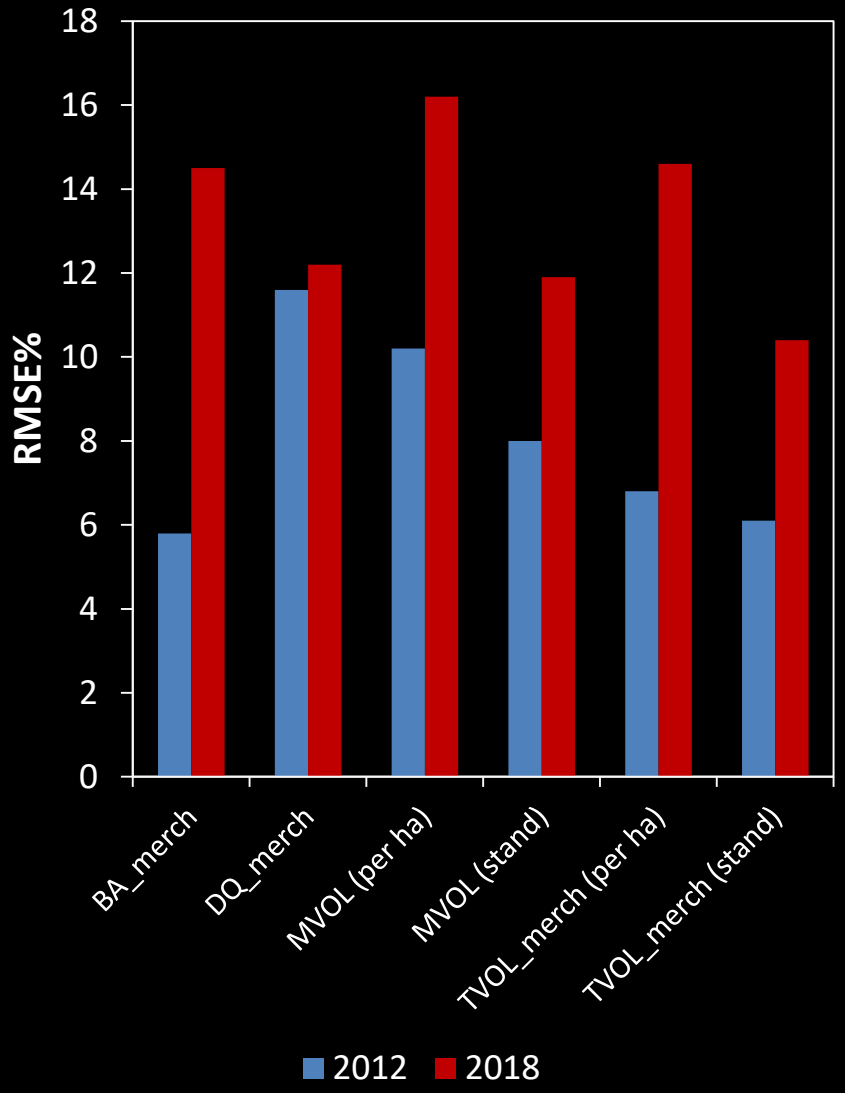
- 27 stands cruised on a 50m grid in spring 2019 (0 years post LiDAR acquisition)
- 10 forest types x 3 stands identified. Post-cruising species information realigned sampling by forest types

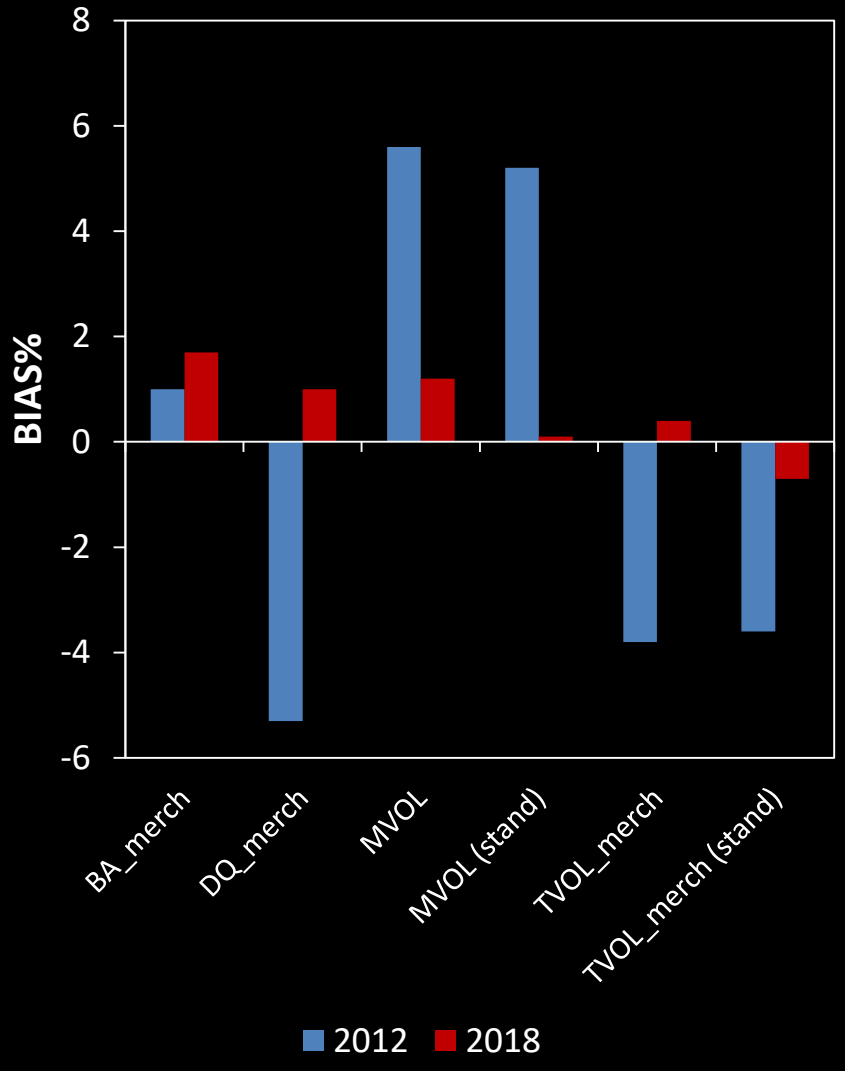
4 X Pine Natural	**4 X Red Pine Plant**	**3 X Tolerant Hwd**	**4 X Mixedwood**
2 X Oak	**2 X Black Spruce**	**1 X Lowland Conifer**	**2 X Jack Pine**
2 X Poplar	**3 X Pine Managed**		

2018 validation stands

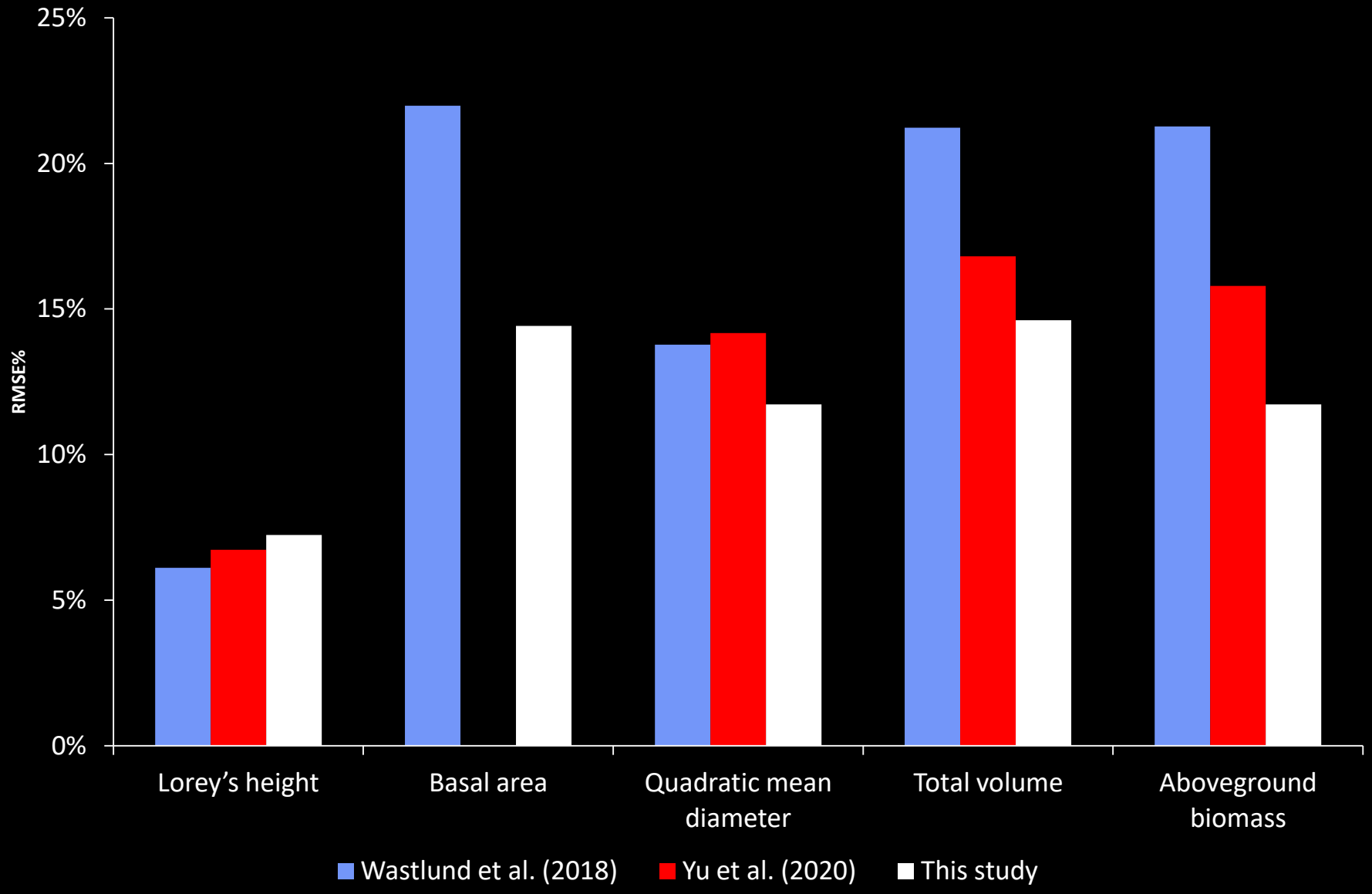


EFI outcomes: 2012 LML vs 2018 SPL



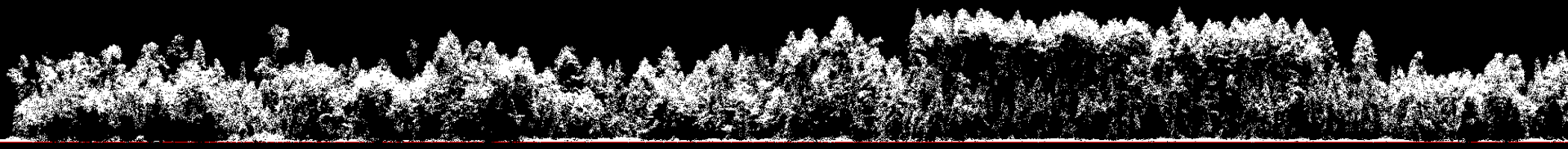


EFI outcomes: Comparisons to other studies



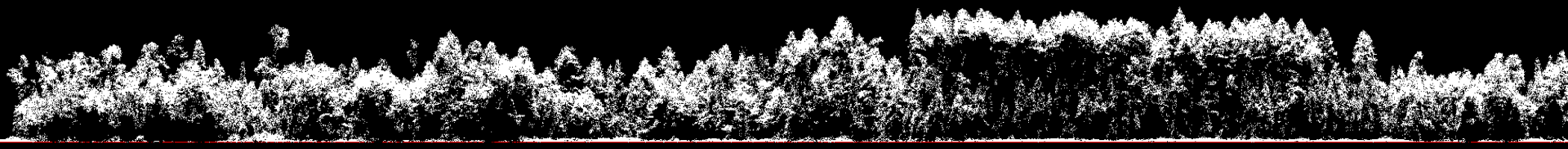
Summary (inventory)

- Area-based models developed using SPL data produced accurate inventory attribute estimates with minimal bias



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



Summary (inventory)

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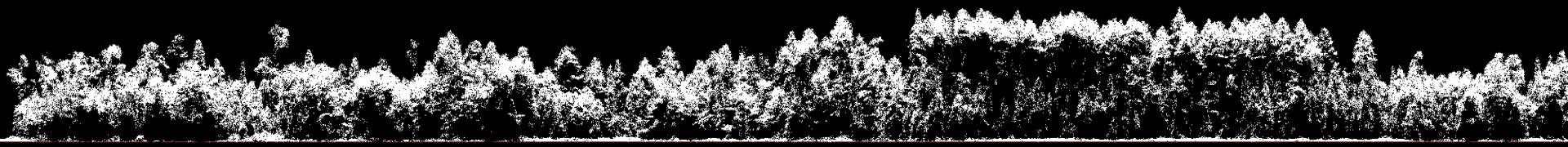
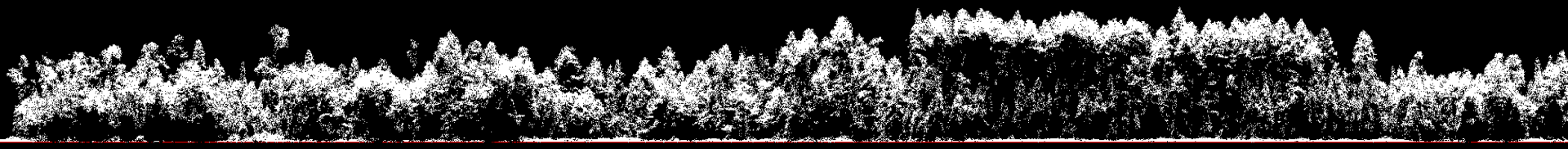
- Accuracy varies by forest type, with greatest overestimation for managed white pine stands and the greatest underestimation for red pine plantations



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*, 97(1): 78–96. https://doi.org/10.5558/tfc2021-009

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

Les données de levés laser aéroportés (ALS; LiDAR) deviennent une source de données forestières de plus en plus commune et certaines juridictions intègrent déjà de façon opérationnelle les données ALS aux mesures obtenues sur le terrain. À mesure que la technologie se développe, divers capteurs LiDAR pourraient amener de nouvelles avenues pour l'intégration des données LiDAR aux protocoles d'inventaire forestier. Le LiDAR simple photon (SPL) permet d'acquérir des données efficacement sur de vastes étendues et mérite qu'on s'y intéresse davantage comme outil d'inventaire forestier. Dans cet article, nous avons vérifié s'il était possible d'estimer les paramètres d'inventaire forestier dans des forêts mélangées de la zone des Grands Lacs et du St-Laurent du Sud de l'Ontario (Canada) à partir de données SPL prises sur des arbres en feuilles, combinées à 269 placettes de terrain. Les estimations des paramètres d'inventaire à l'échelle du peuplement ont été validées à partir de données de référence indépendantes, acquises dans 27 peuplements échantillonnées intensivement. Nous avons ainsi estimé la hauteur totale, la hauteur de Lorey, le volume brut et des tiges marchandes, le volume marchand des tiges, la surface terrière, le diamètre moyen quadratique ainsi que la biomasse épigée totale avec une erreur quadratique moyenne de 13,52 %, 7,24 %, 14,61 %, 16,27 %, 14,42 %, 12,25 %, et 11,72 %, respectivement. L'erreur relative a été < 1 % pour tous les paramètres à l'exception de la hauteur totale (10,34 %), du volume marchand (3,37 %) et de la surface terrière (1,68 %). La précision et le biais variaient selon le type de forêt et des validations à l'échelle du peuplement ont été nécessaires pour évaluer la performance du modèle dans différentes conditions de peuplements. Il en ressort que les données SPL peuvent être utilisées pour obtenir des résultats précis d'inventaire forestier par surface dans les forêts mélangées comportant plusieurs essences et un historique d'aménagement complexe.

Mots-clés: Inventaire forestier amélioré, LiDAR, forêt tempérée, ALS, LSP, IFA, FRP

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[2]Forest Analysis Ltd., 1188 Walker Lake Dr., RR4, Huntsville, ON P1H 2J6, Canada
[3]Retired – Natural Resources Information Section, Science and Research Branch, Ontario Ministry of Natural Resources and Forestry, 3301 Trout Lake Road, North Bay, Ontario, P1A 4L7, Canada

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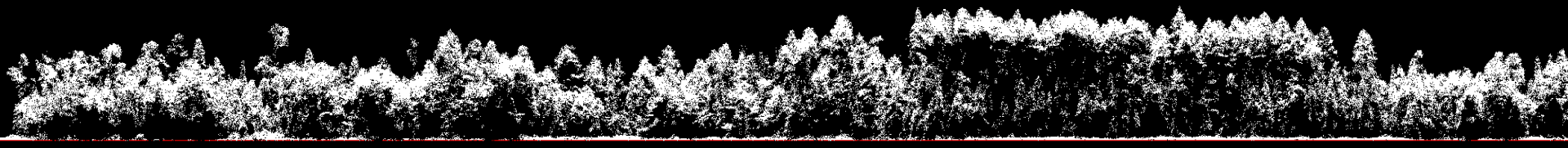
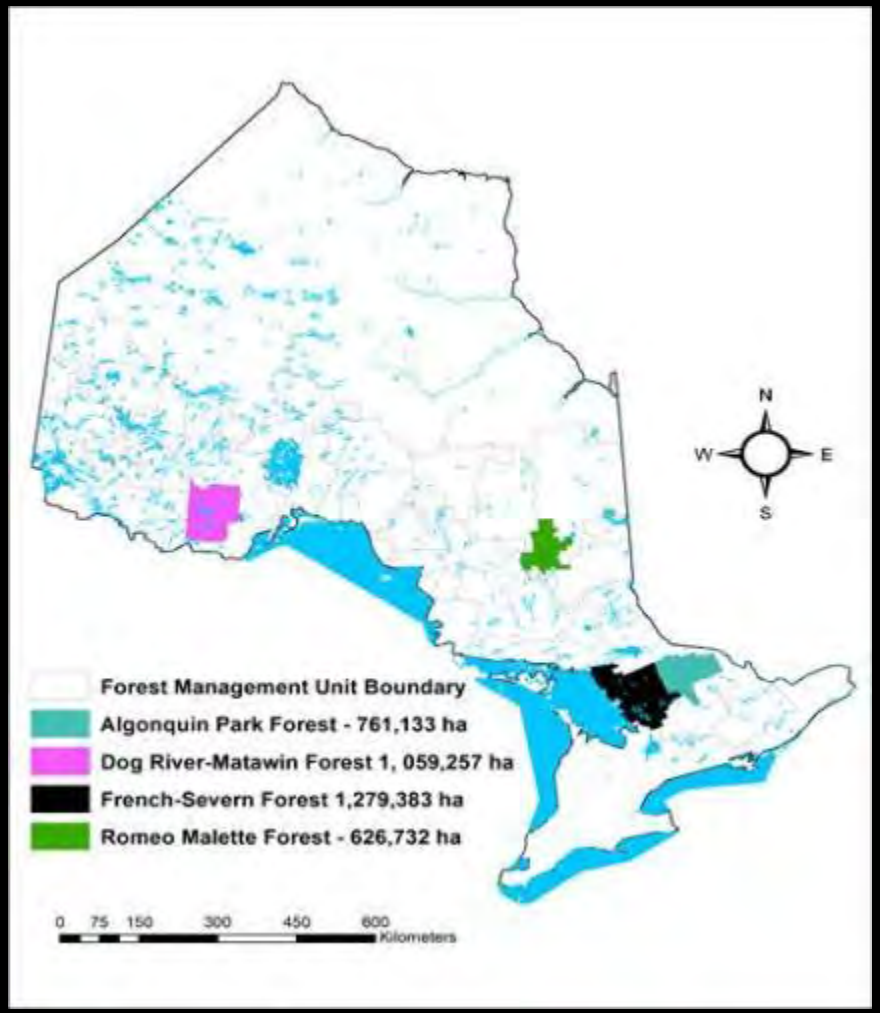
Conclusions

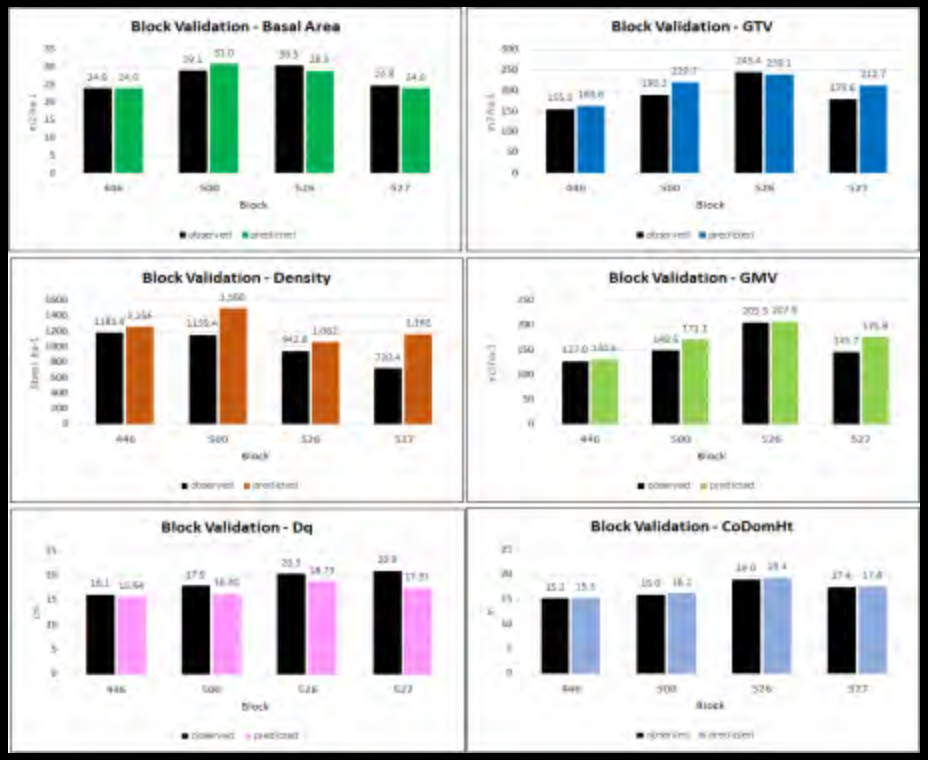
Leaf-on SPL data can be used to:

1. characterize terrain surface elevations under a range of forest conditions, but with lower accuracy (but still within requirements for CQL1);
2. generating area-based models of forest inventory attributes with accuracy that is on par with that achieved using LML



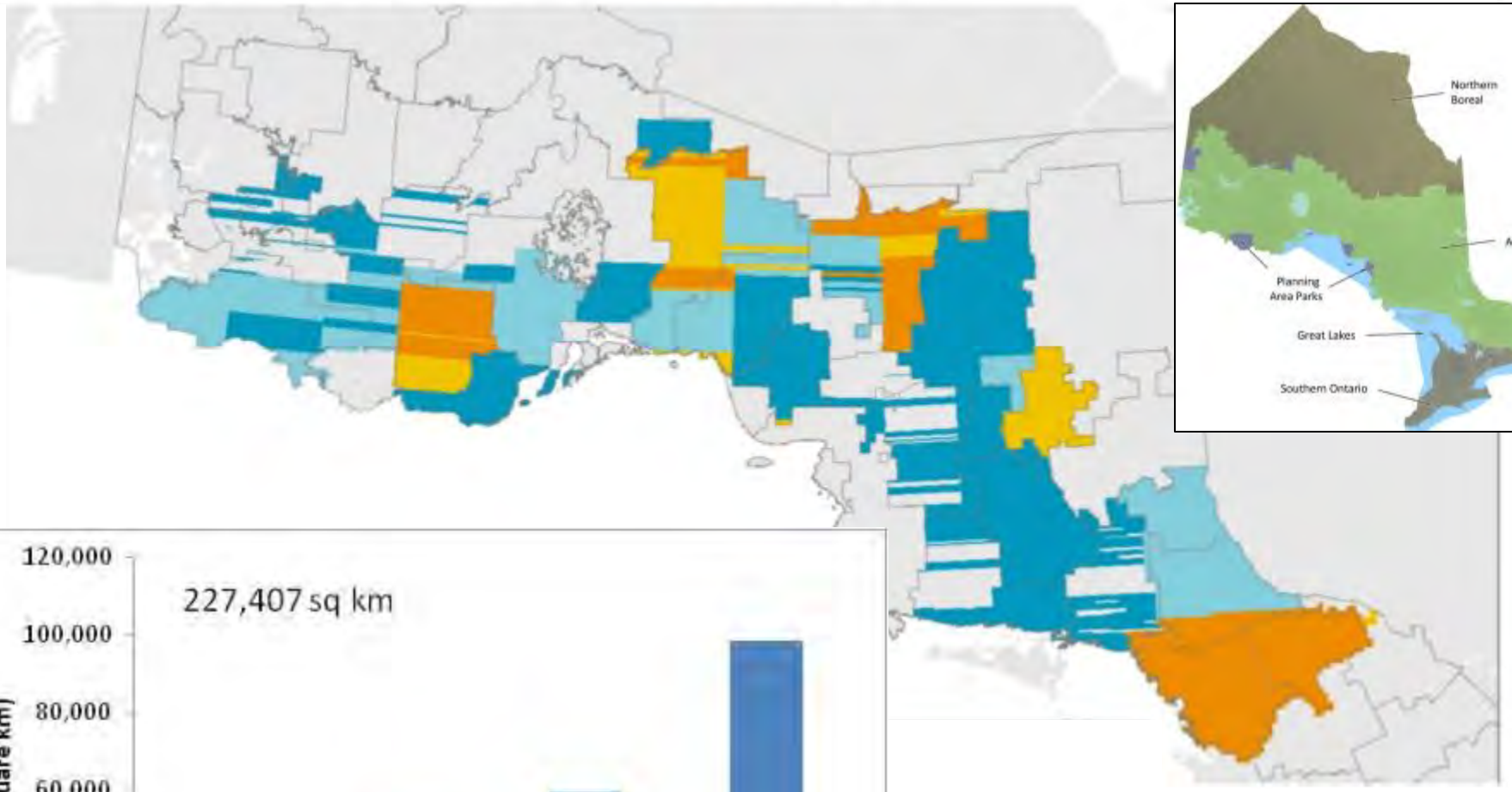
Next steps?

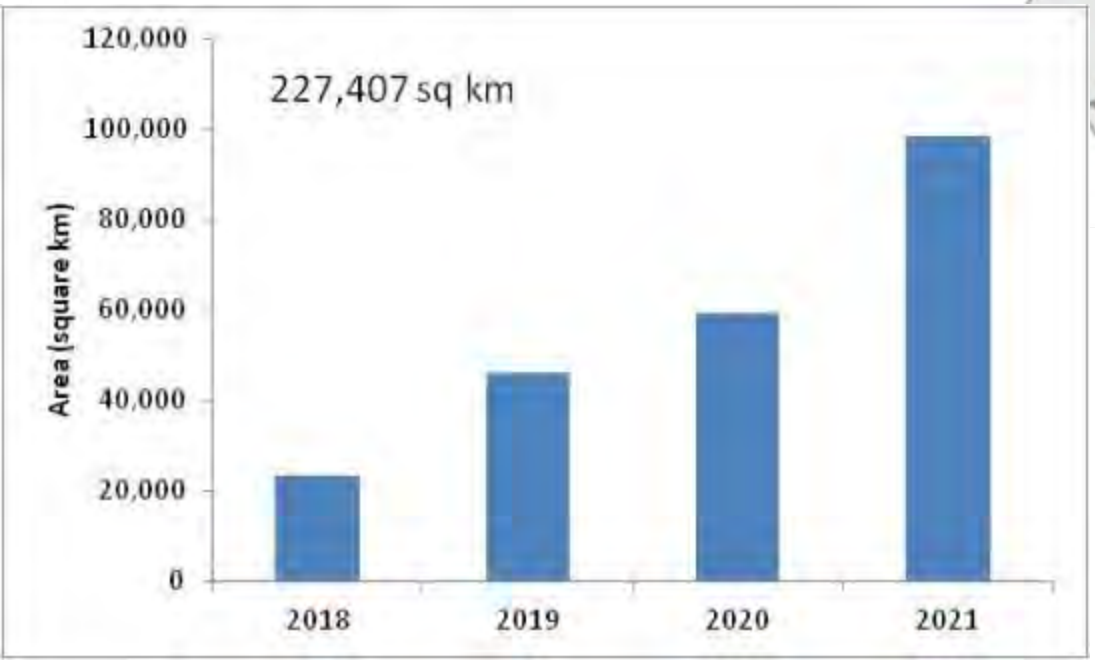




- Apply insights gained at PRF
- Accelerate operational implementation
- Standardize/streamline tools and protocols for data processing (field & lidar) and model development on the cloud

SPL data acquisition in Ontario's manged forests





Source: I. Sinclair, NDMNRF

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2021, VOL. 12, NO. 10, 1049–1060
https://doi.org/10.1080/2150704X.2021.1962575

Taylor & Francis

Single photon lidar signal attenuation under boreal forest conditions

Liam Irwin[a], Nicholas C. Coops[a], Martin Queinnec[a], Grant McCartney[b] and Joanne C. White[c]

[a]Department of Forest Resources Management, University of British Columbia, Vancouver, British Columbia, Canada; [b]Forest Information Systems, Rayonier Advanced Materials, Timmins, Ontario, Canada; [c]Canadian Forest Service (Pacific Forestry Centre), Natural Resources Canada, Victoria, British Columbia, Canada

ABSTRACT

Single-photon lidar (SPL100) is a recently commercialized airborne lidar system facilitating efficient wide-area acquisitions of high-density point clouds due to its capacity for higher altitude acquisitions compared to traditional linear-mode lidar (LML) systems. Increased acquisition efficiency and point densities make SPL100 attractive for forest management applications. SPL100 utilizes 532 nm (green wavelength) lasers, wherein there is reduced reflectance from vegetation, increased sensitivity to solar noise, and increased signal attenuation, which may impact the vertical distribution of SPL100 returns in forest canopies. We assessed SPL100 data acquisitions over managed forests in north-eastern Ontario, Canada, using high-density unmanned aerial vehicle-borne laser scanning (ULS) data as reference over a range of forest conditions with variable vertical structure. Signal attenuation depth of individual SPL100 returns was estimated through a surface model normalization approach stratified by a ULS-derived structural index that compared densities of returns in the upper canopy to low vegetation and near ground. Canopy signal attenuation was closely matched in both systems, particularly in the upper canopy and near the ground surface; however, results showed a 31% reduction in the relative characterization of mid-canopy vegetation layers by SPL100 under conditions identified by the structural index as closed canopy, compared to the ULS system.

ARTICLE HISTORY
Received 11 May 2021
Accepted 27 July 2021

1. Introduction

The Leica SPL100 is a single-photon light detection and ranging (lidar) sensor that enables increased spatial coverage and higher point density products when compared to conventional linear mode lidar (LML) systems (Stoker et al. 2016; Swatantran et al. 2016). SPL100 utilizes a 10 × 10 array to split emitted laser pulses into 100 low-powered 'beamlets'. Returning beamlet photons are captured by a highly sensitive 10 × 10 array of detectors that are capable of recording returned energy from single photons. Unlike most vegetation and terrain focused LML systems that emit pulses of near-infrared

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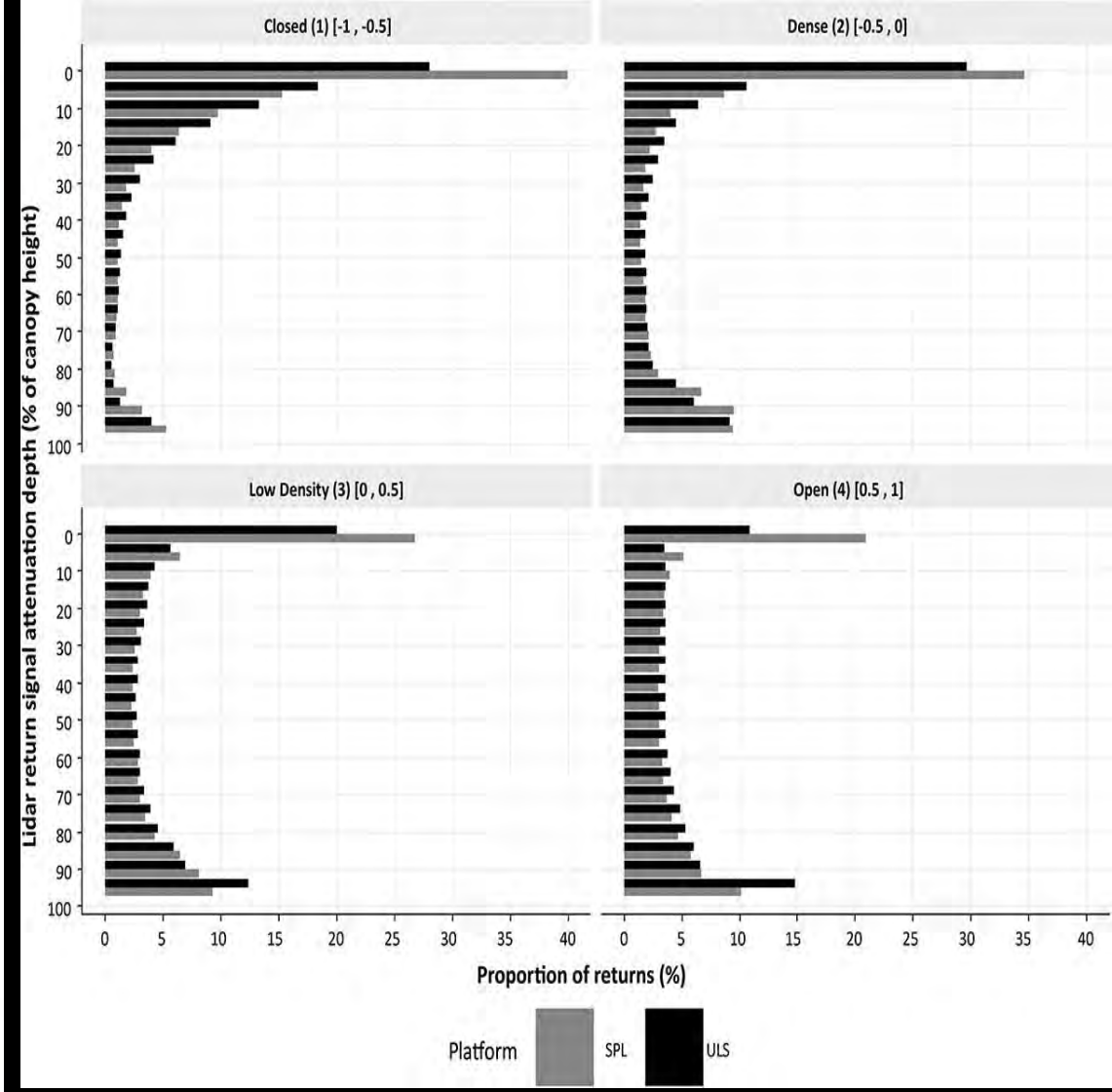

UAV: 1264 points/m2, totalling 9.44 hectares

SPL100 produced 31% fewer relative returns between 20% and 80% of canopy height when compared to the ULS system.

https://doi.org/10.1080/2150704X.2021.1962575

Thank you!

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

Joanne White, Research Scientist

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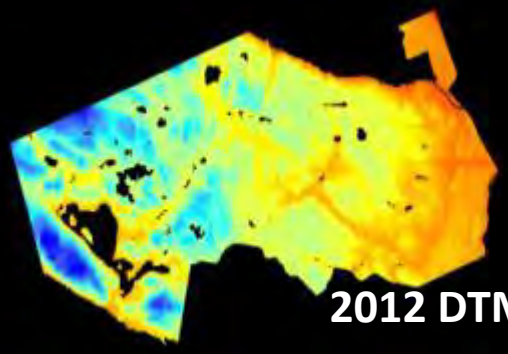
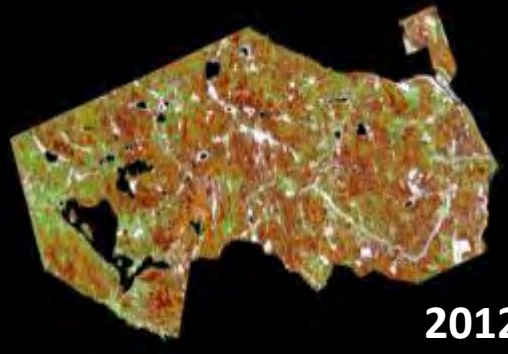
@Joanne_C_White #CFSEFI



2012 DTM



2012 CHM

2013 Vexcel Ultracam

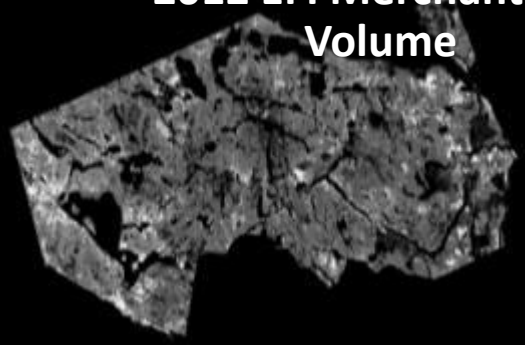
Petawawa Research Forest: Remote Sensing Supersite

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

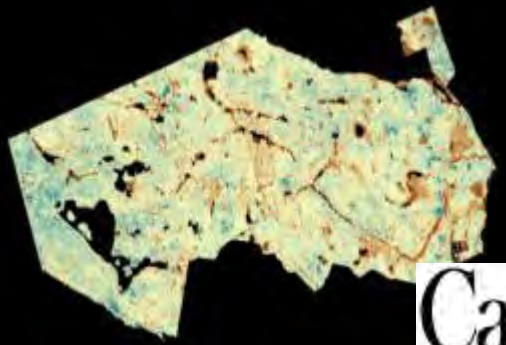
SPL: https://opendata.nfis.org/downloads/petawawa/Raster/LiDAR_2018/PRF_LiDAR2018_LAS.zip

2007 Forest Inventory

2012 EFI Merchantable Volume



2012 EFI Mean Height



Canada