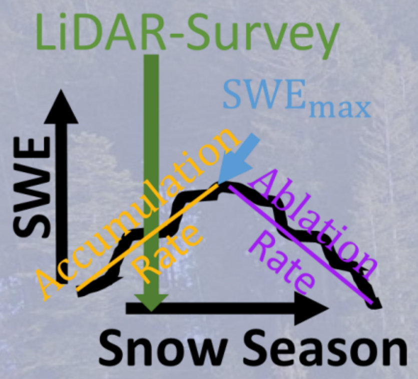
Machine Learning and LiDAR Snowheight Maps from UAVs Reveal Clusters of Snow Variability in a Sub-Alpine Forest

Joschka Geissler[1], Lars Rathmann[1,2], Markus Weiler[1]

[1]University of Freiburg, Germany, [2]Fraunhofer Institute for Physical Measurement Techniques IPM, Freiburg, Germany

Motivation



Data

Methods

Unsupervised Classification of LiDAR HS* Maps

Assignment of HS* timeseries

Model snow density using HS* timeseries

Results

Cluster of spatio-temporal snow variability

Daily maps of HS* and SWE*

*HS= Snow Depth [m]
SWE = Snow Water Equivalent [mm]

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Motivation | Data | Methods | Results

Unsupervised Classification of LiDAR HS Maps

Assignment of HS timeseries

Model snow density using HS timeseries

Cluster of spatio-temporal snow variability

Daily maps of HS and SWE

Red Frame?
Click on me!

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For-ward

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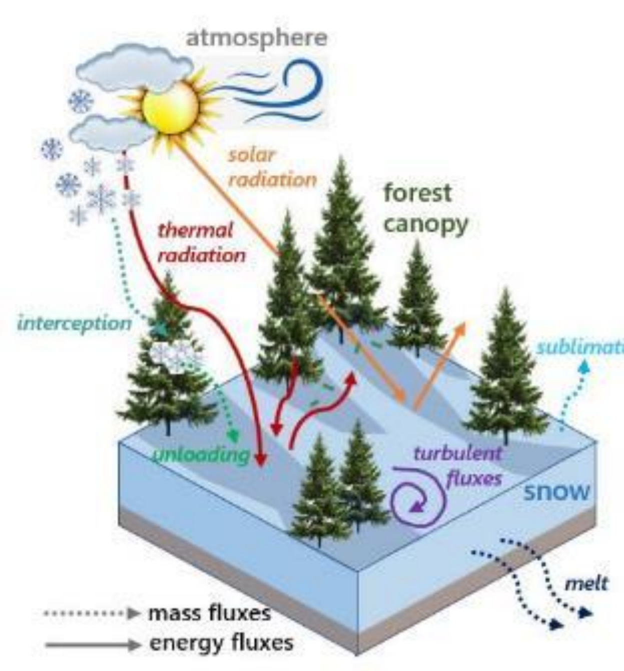
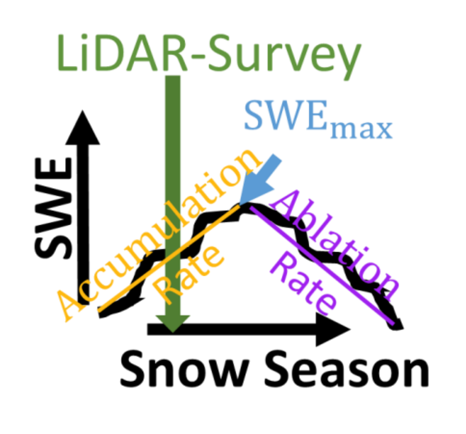
Motivation – Why Snow in Forests?

Canopy snow processes

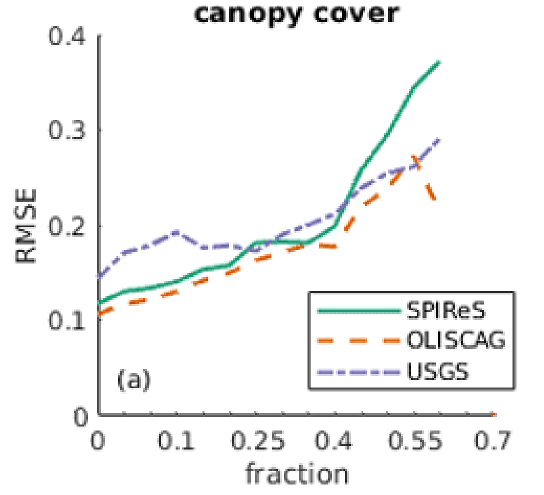


Mazzotti et al. (2020)

Validation of snow models



Validation of satellite products



Modified from Stillinger et al. (2023)

- Forests have a high spatial variability of snow and complicate remote sensing data acquisitions
- Snow models of all scales lack validation data of seasonal snow parameters
- Errors increase with forest cover for (passive optical) satellite snow products (e.g. Landsat 8 products)
- **Temporally and spatially continous validation data for forested environments is needed**

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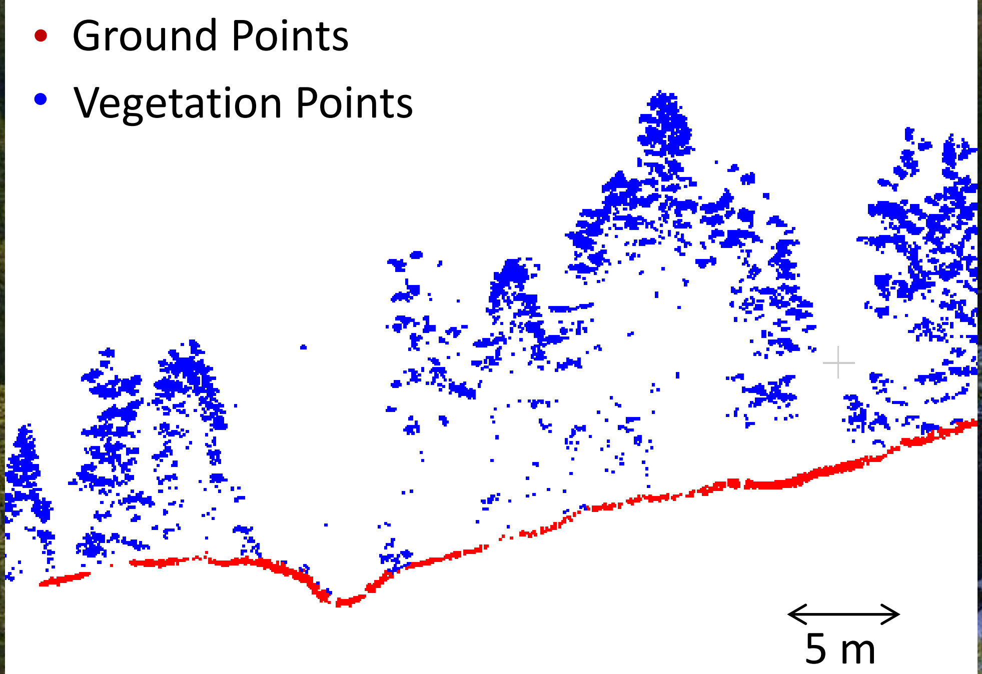
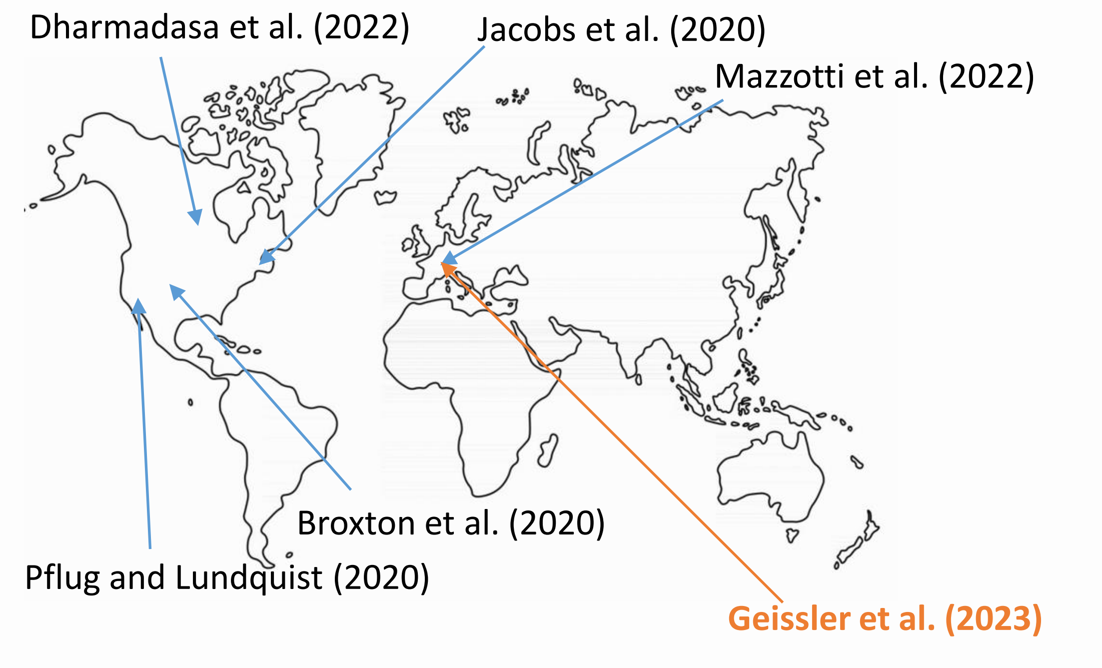
Motivation – Why LiDAR?

Sub-canopy snow mapping



Recent snow distribution datasets from LiDAR remote sensing



- ➢ Potential to map snow under forest canopy (Harder et al. 2020)
- ➢ Increasing Data Availability

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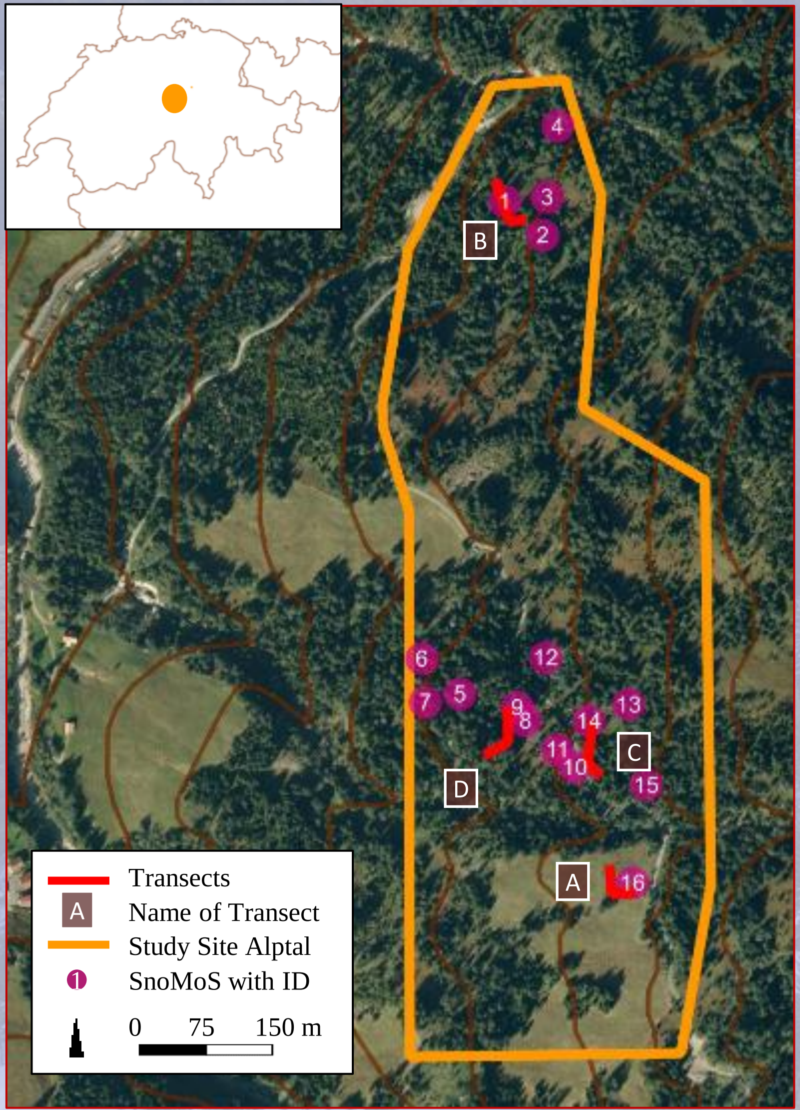
Data



Study Site

- 0.22 km²
- Minor influence of topography: West-facing hillside at 1200m (±35m)
- Heterogenous coniferous forest with heights of up to 35 m

Data

- 16 SnoMoS
- 8 UAV-based LiDAR Surveys (905 nm; Point density approx. 250 P/m²)
- 4 x 50 m transects x 9 manual Snow Surveys

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UAV + LiDAR

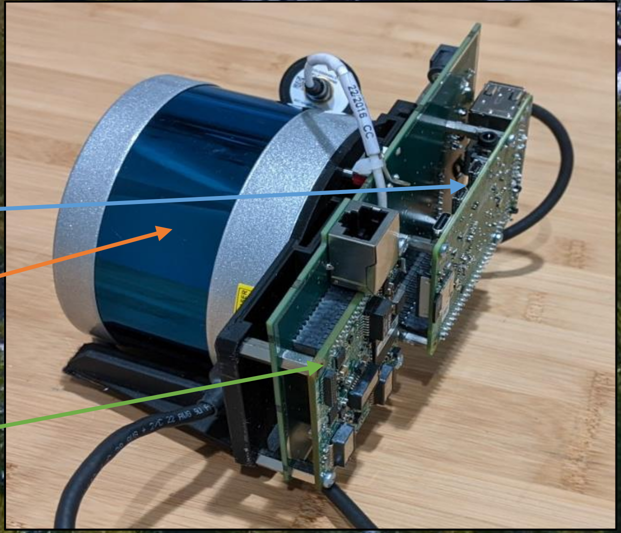
LiDAR System

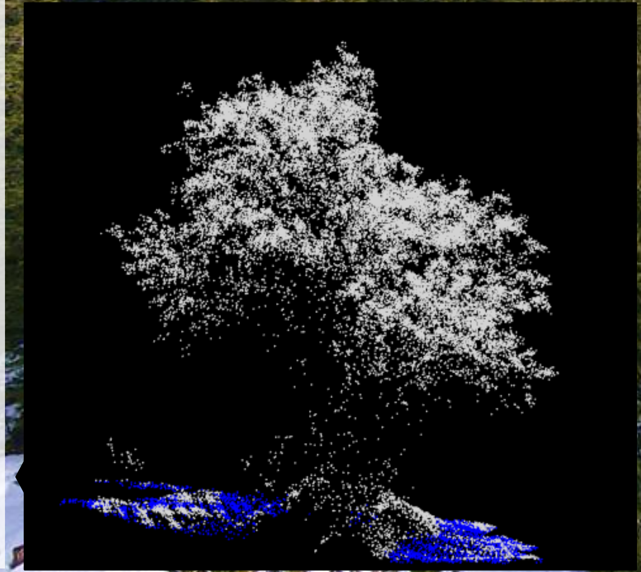
UAV:
DeltaQuad Pro VTOL Fixed Wing

Computer
Raspberry Pi Zero WH v.1.1

LiDAR:
Velodyne Puck LITE
(Dual Return, 905 nm)

IMU
Applanix APX – 15
On-Board





LiDAR Data and Mission:

- Altitude: 80 m above ground
- Flight speed: 19 m/s.
- 37 km in 33 minutes
- 40% Battery charge remaining
- 16 m distance between flightlines.
- Average Point density:
  - Overall: 250 P/m² [2x125 P/m²]
  - Ground Points
    - Open: 223 P/m²
    - Forest: 45 P/m²

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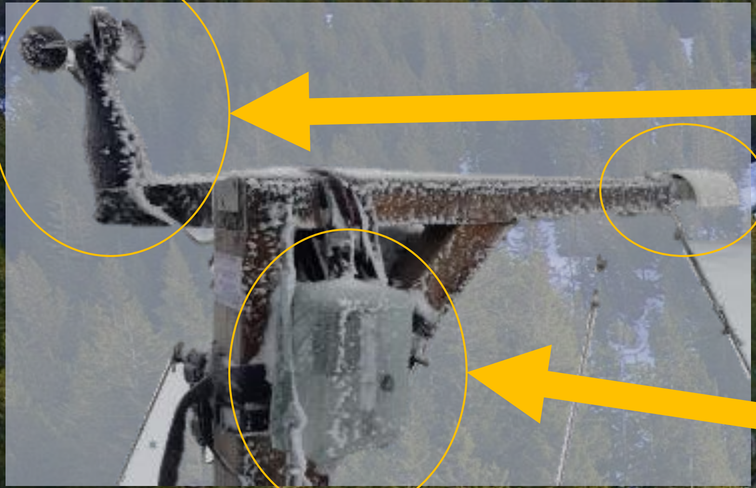
SnoMoS



- **Wind**: 3 Cup wind anemometer
- **Sensor**: Shortwave radiation (IN), longwave radiation (out), humidity, air temperature and ultrasonic snow depth
- **Logger**
- **Time-Lapse Camera** for gap filling

Pohl S., **Gravelmann** J., **Wawerla** J. & **Weiler** M. (2014): Potential of low-cost sensor network to understand the spatial and temporal dynamics of a mountain snow cover, Water Resour Res, 50, doi:10.1002/2013WR014594

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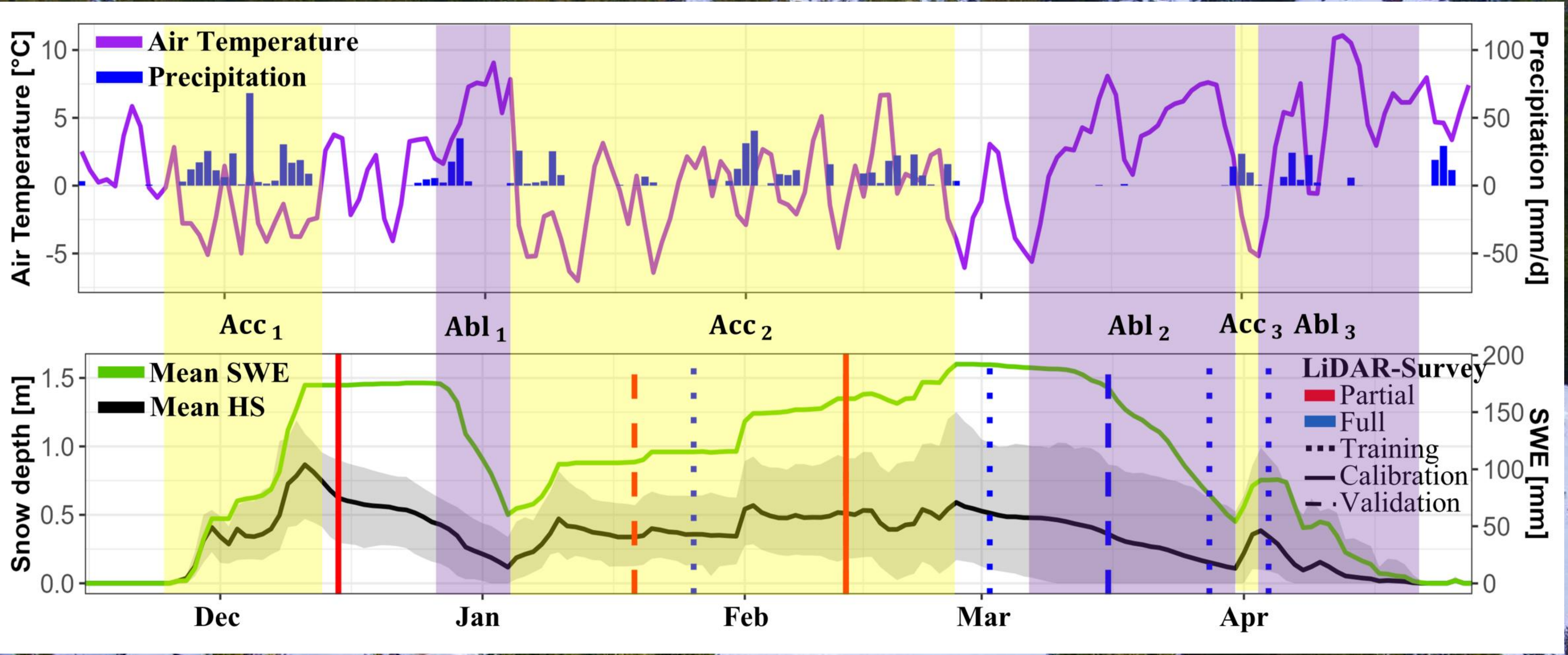

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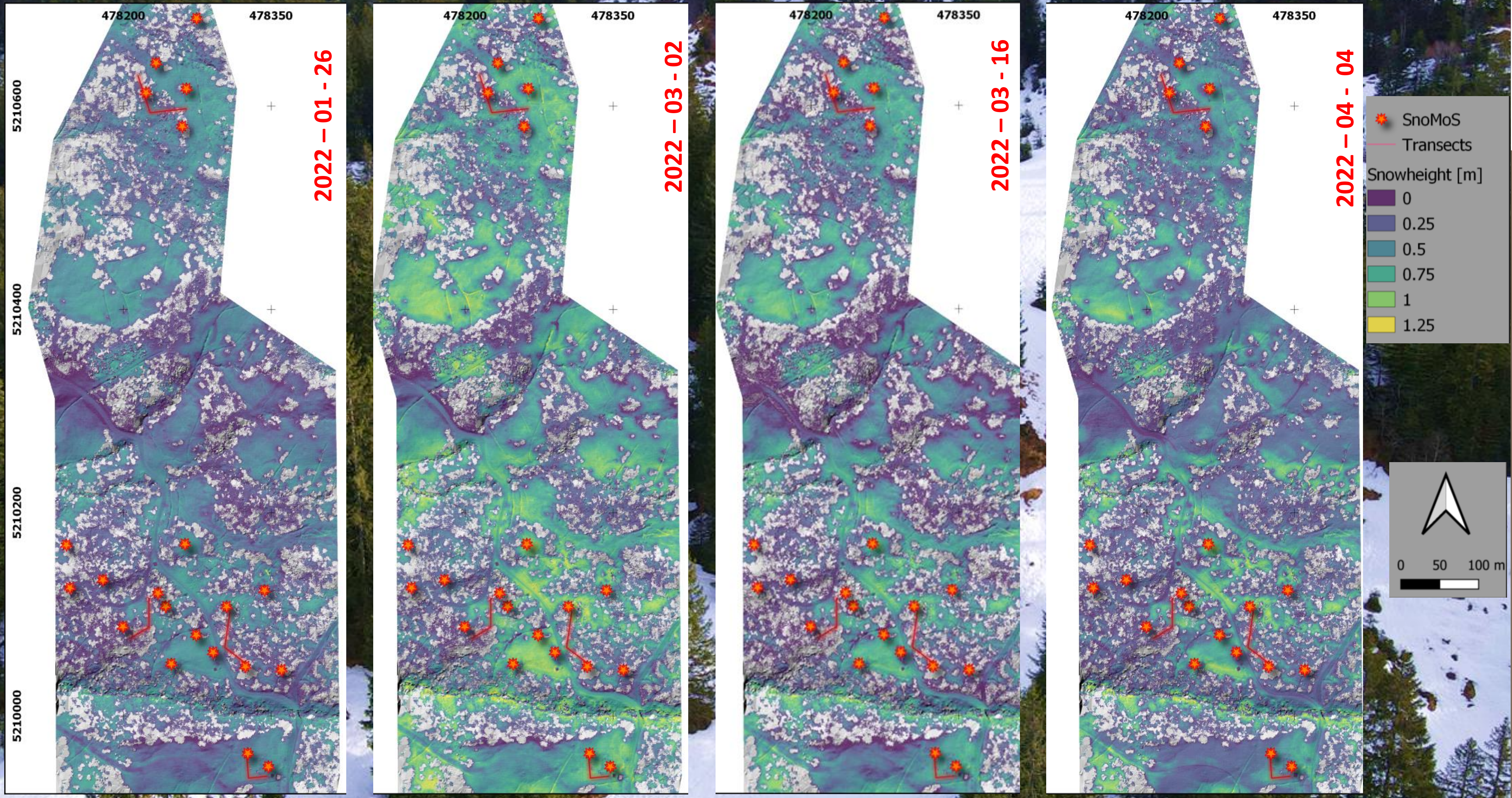
LiDAR – HS Maps



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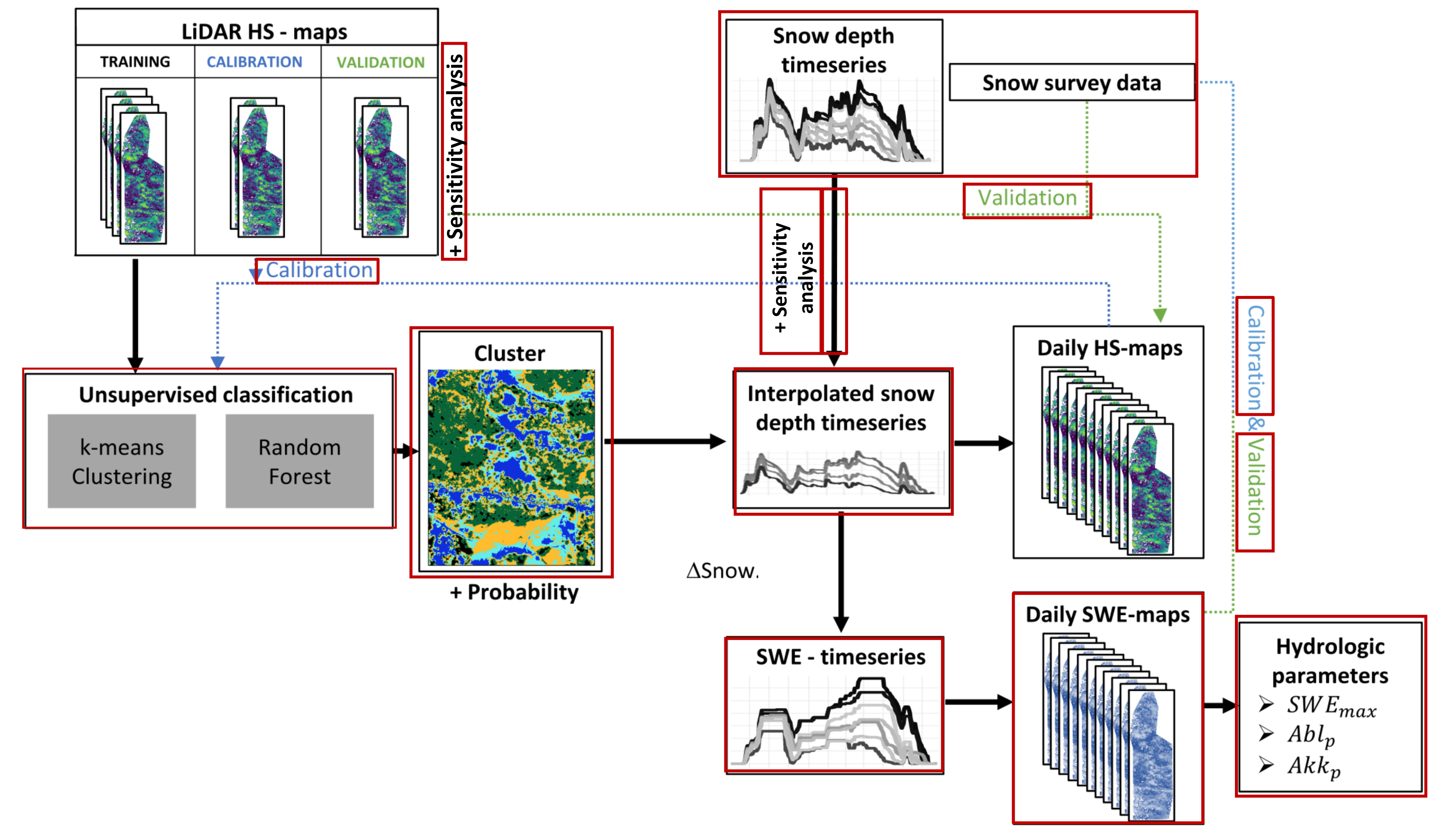
Methods



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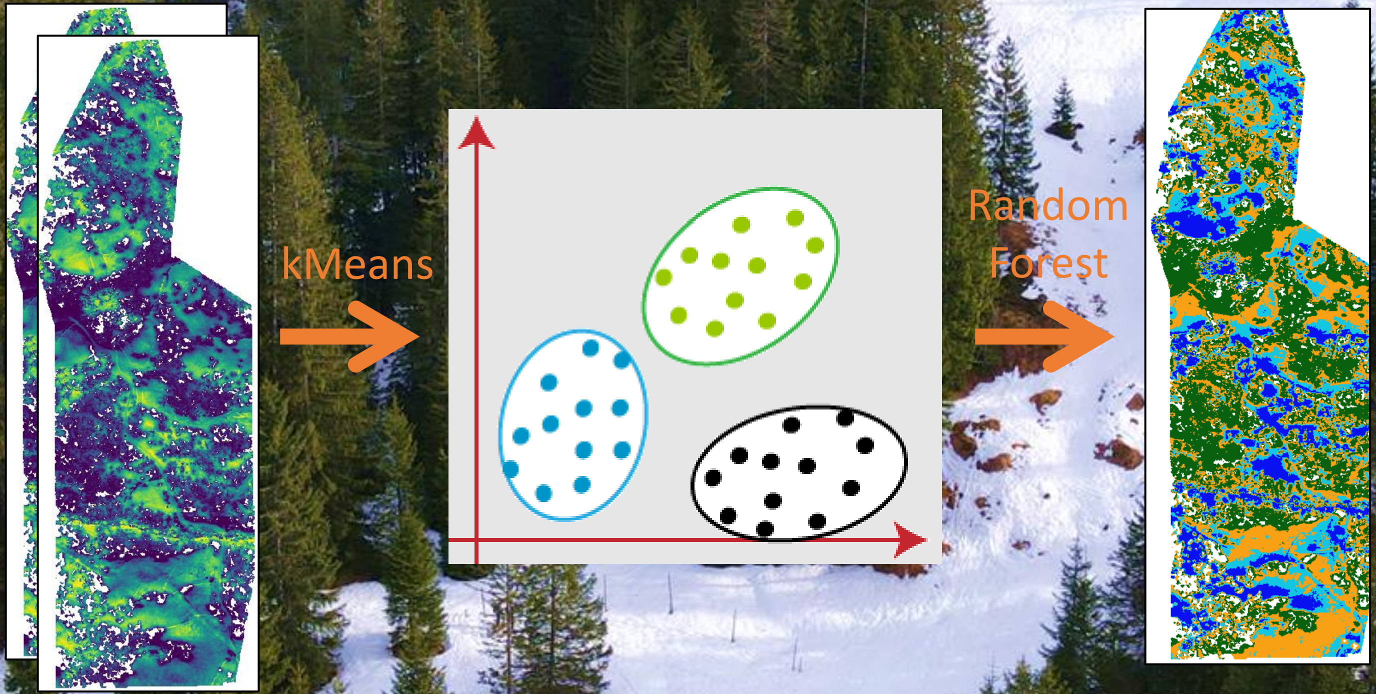
Unsupervised Classification of LiDAR HS Maps

i) Randomly choose n_sample training data points for the kMeans Algorithm.
ii) Apply the kMeans Algorithm to find n_class cluster.
iii) Use the kMeans Output to train a random forest model.
iv) Predict cluster for the whole dataset using the trained random forest (including probabilities)



Calibration
Sensitivity analysis
See Clusters

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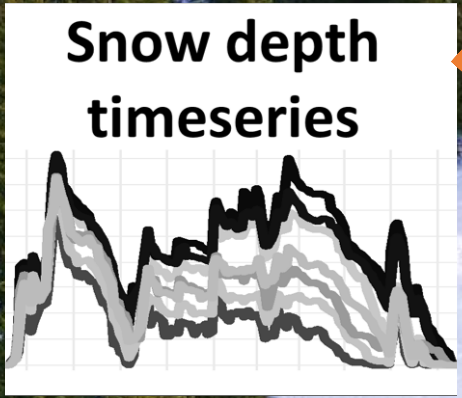
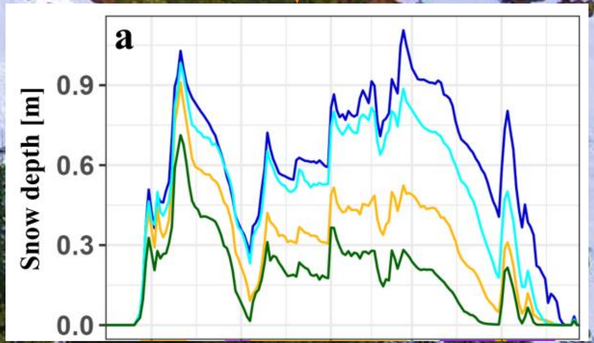
Assignment of HS timeseries

Get probabilities of sensor locations s belonging to the clusters c ws,c

Determine the cluster's snow depth at the time t $HS_c(t)$: $HS_c(t) = HS_s(t) \cdot \frac{w_{s,c}}{\sum w_{s,c}}$





Sensitivity analysis

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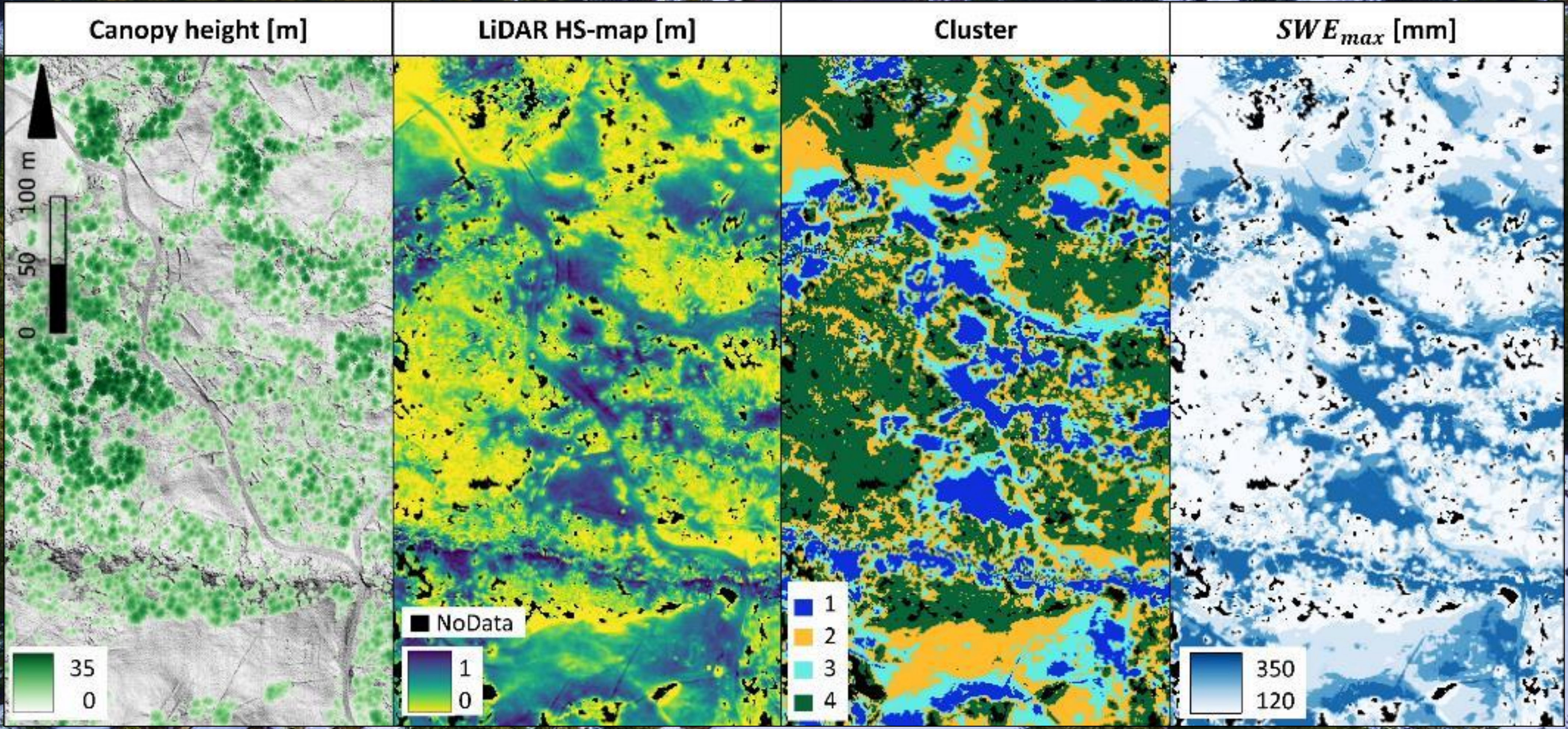
Cluster of spatio-temporal snow variability



See Clusters for other Sites

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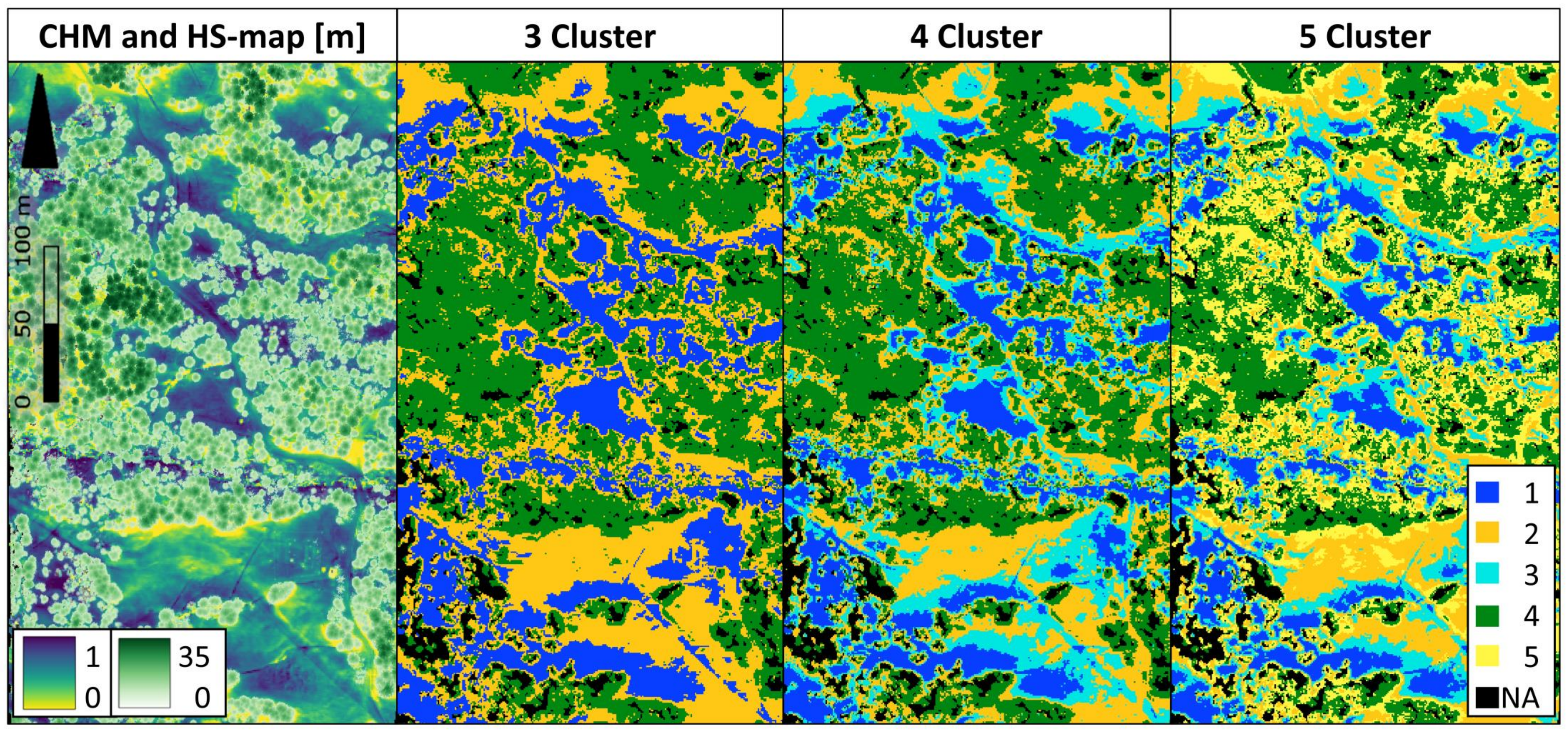
Cluster of spatio-temporal snow variability



Calibration

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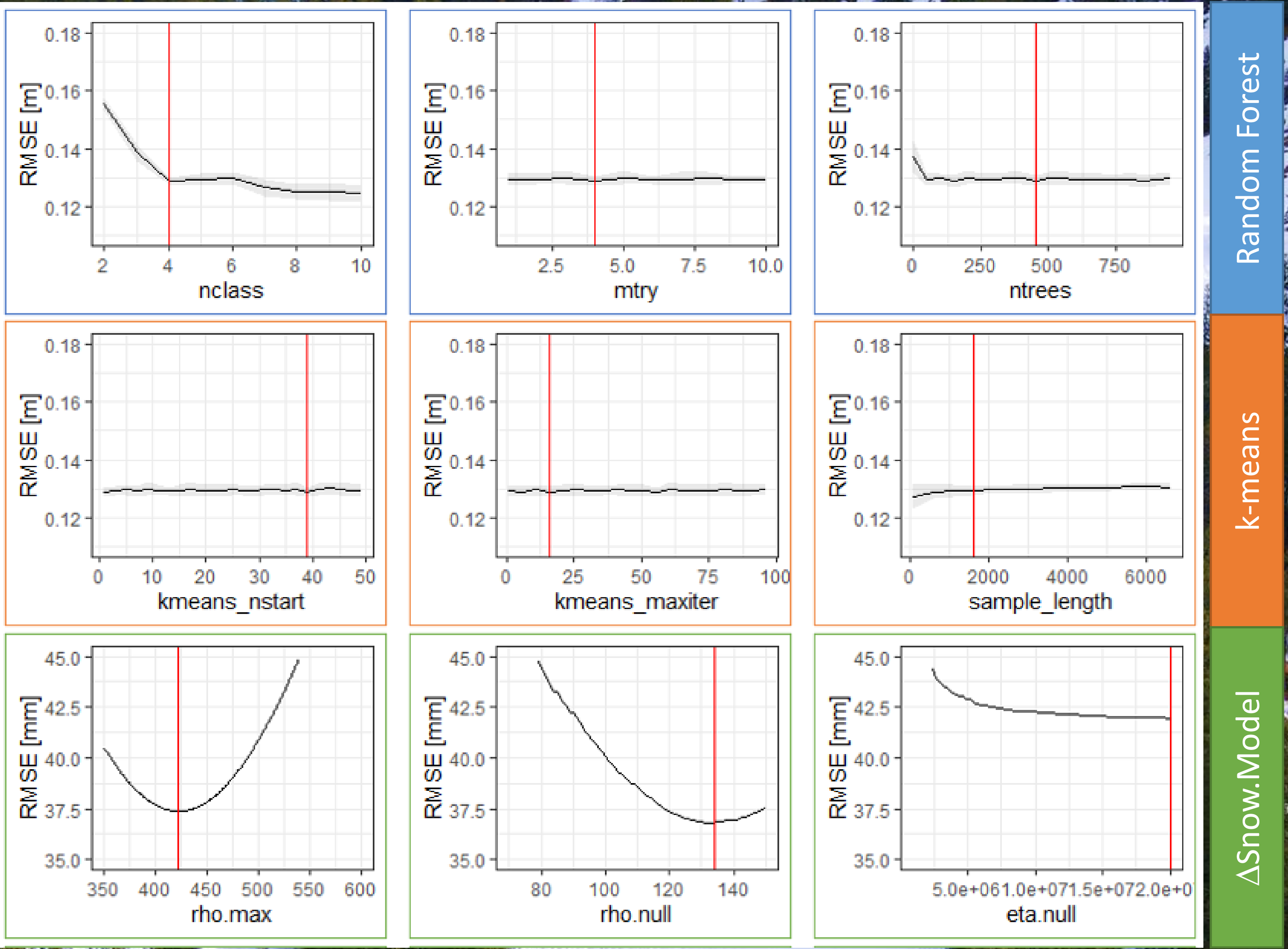
Model Calibration



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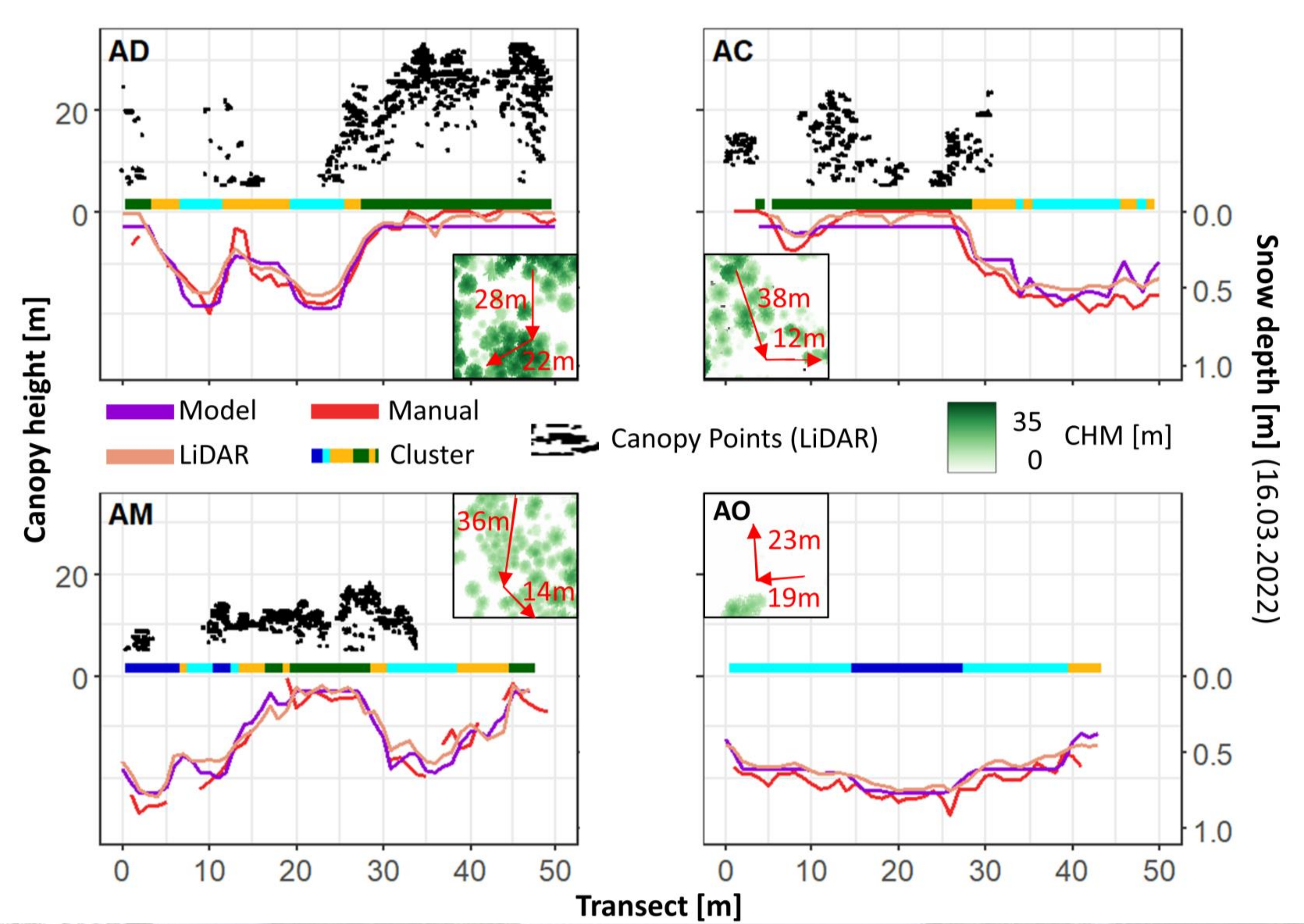
Model Validation



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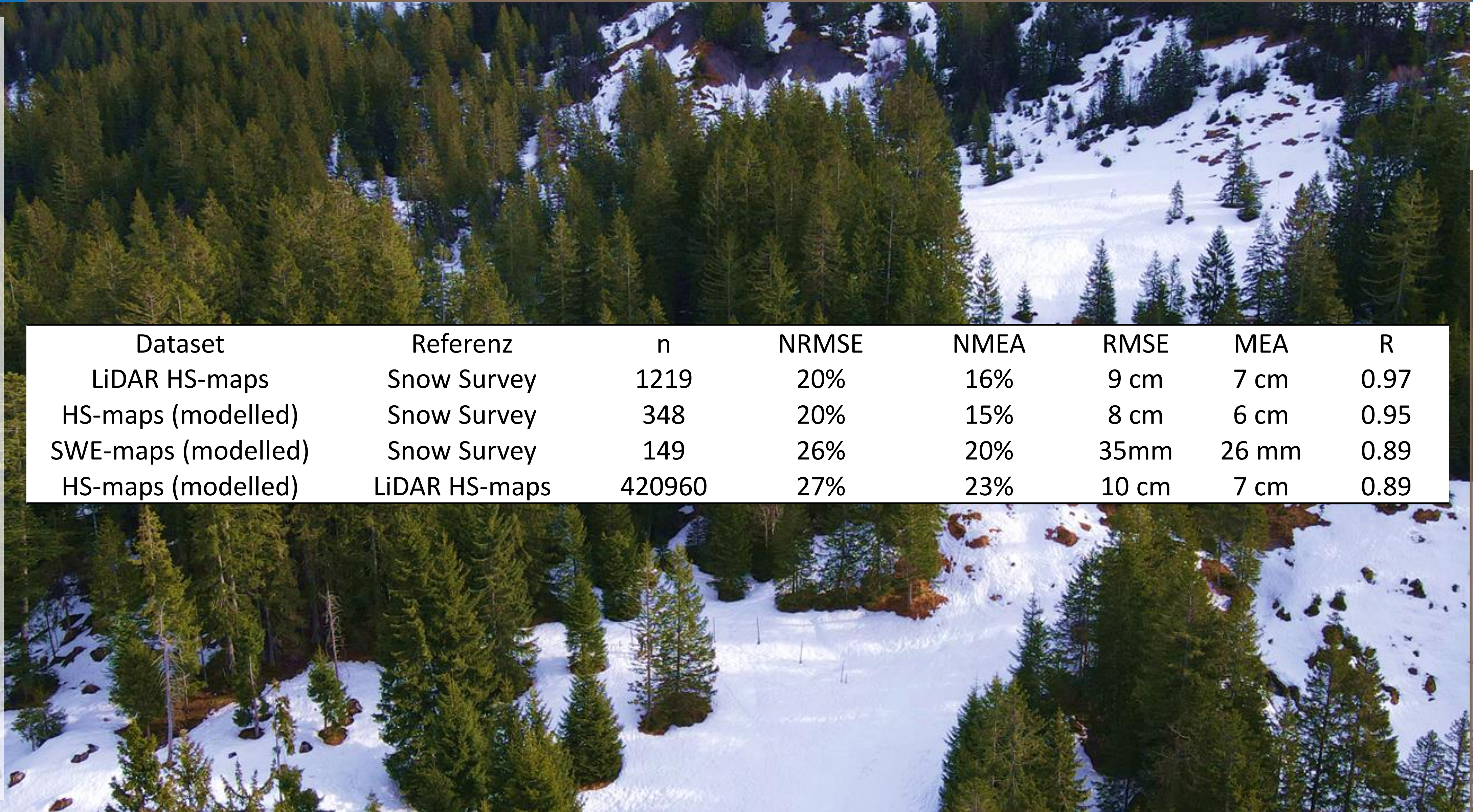

Dataset	Referenz	n	NRMSE	NMEA	RMSE	MEA	R
LiDAR HS-maps	Snow Survey	1219	20%	16%	9 cm	7 cm	0.97
HS-maps (modelled)	Snow Survey	348	20%	15%	8 cm	6 cm	0.95
SWE-maps (modelled)	Snow Survey	149	26%	20%	35mm	26 mm	0.89
HS-maps (modelled)	LiDAR HS-maps	420960	27%	23%	10 cm	7 cm	0.89

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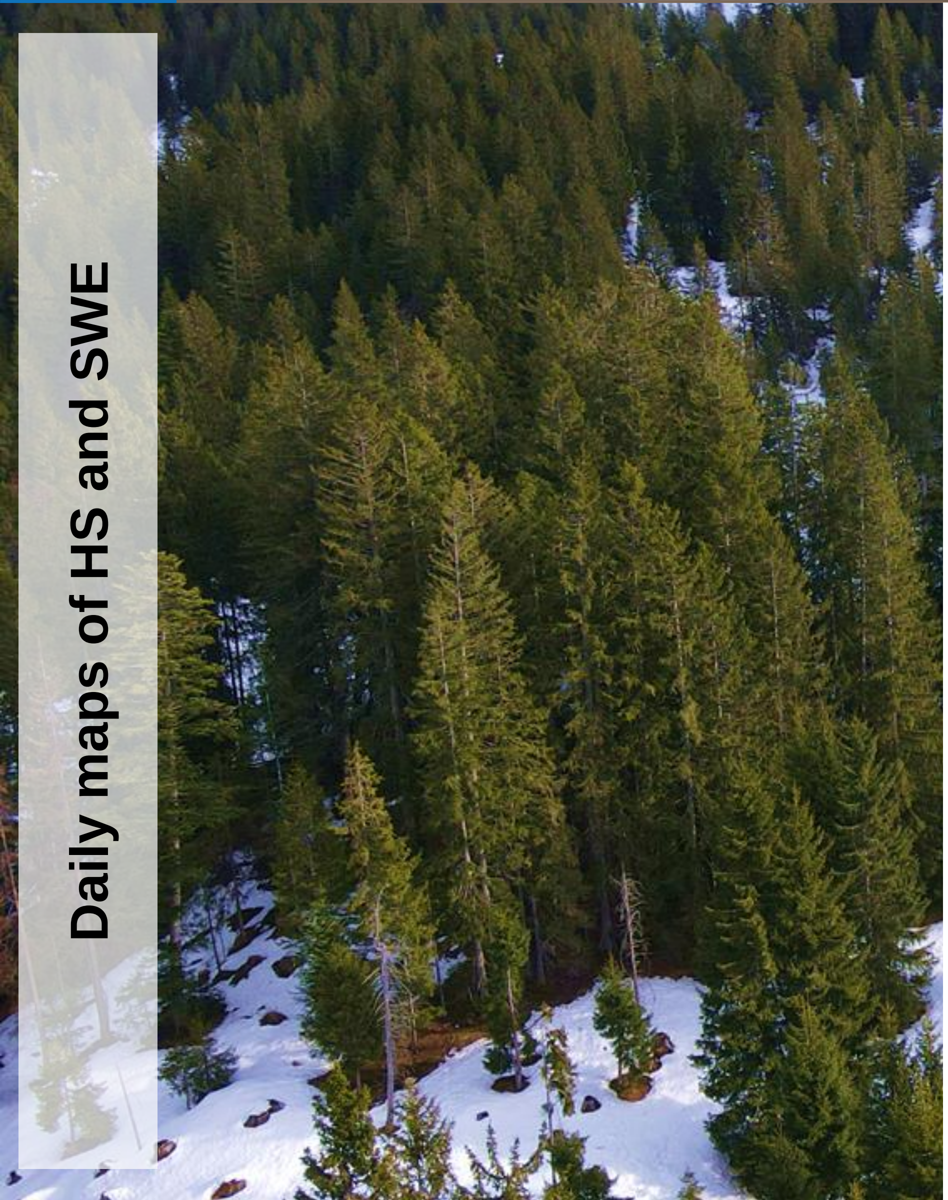
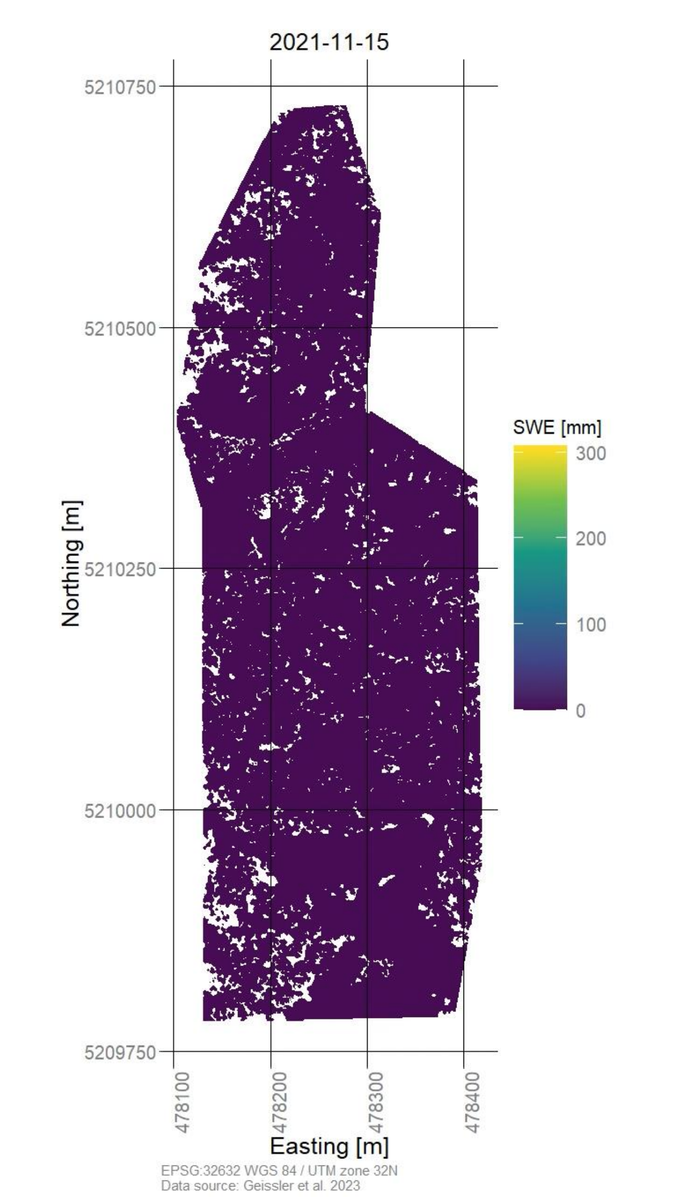
Daily maps of HS and SWE





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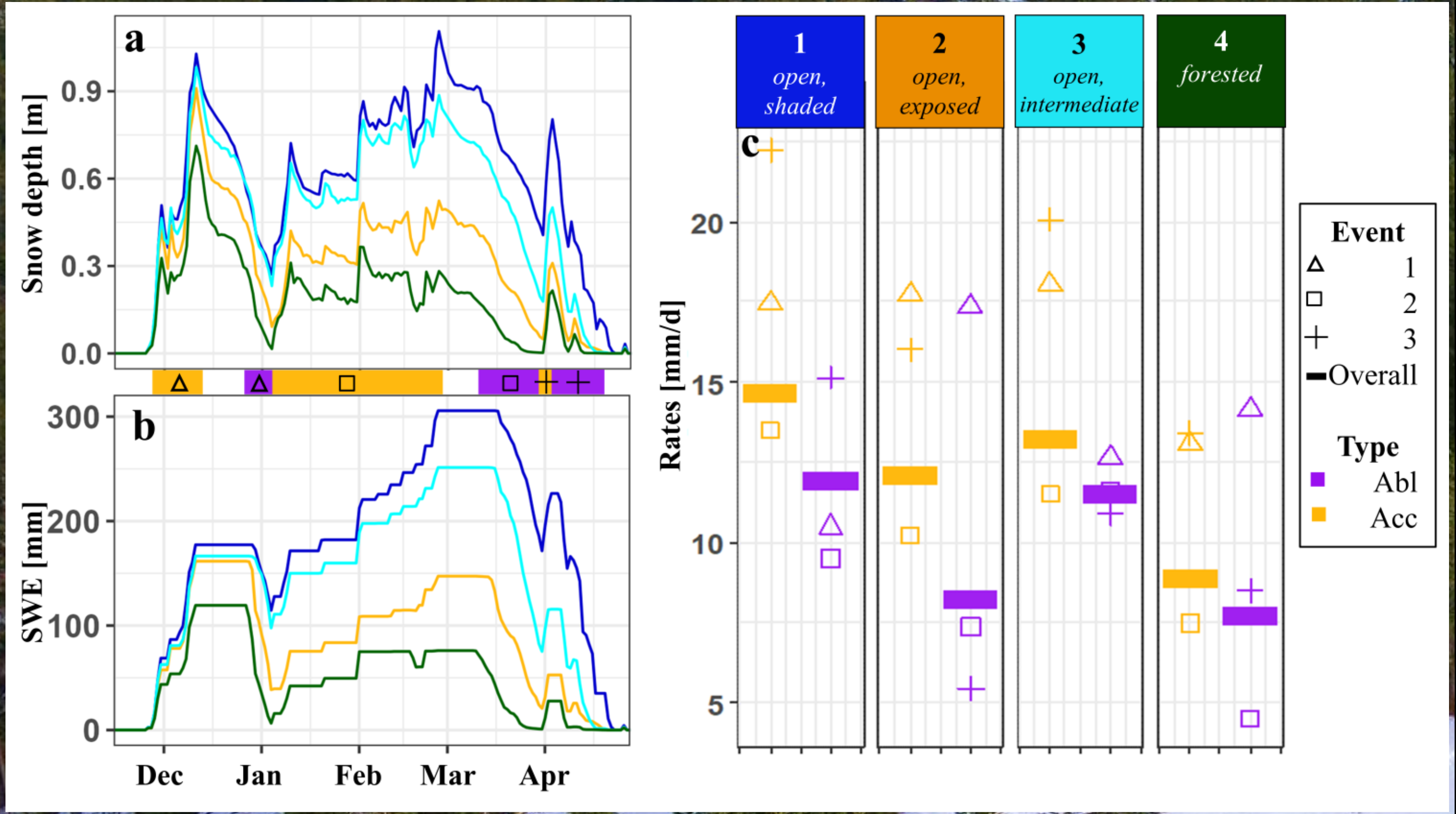

Accumulation

- Overall accumulation reduced by 26% to 39% from open to forested clusters.
- High correlation between accumulation events (R: 0.81-0.83) and to canopy (R: 0.64 (CHM))

Ablation

- Overall ablation rates are reduced in forested and open, exposed cluster by 28% - 36%
- Mid-winter and late-winter RoS show opposite relative ablation rates between the clusters (R:-0.91).

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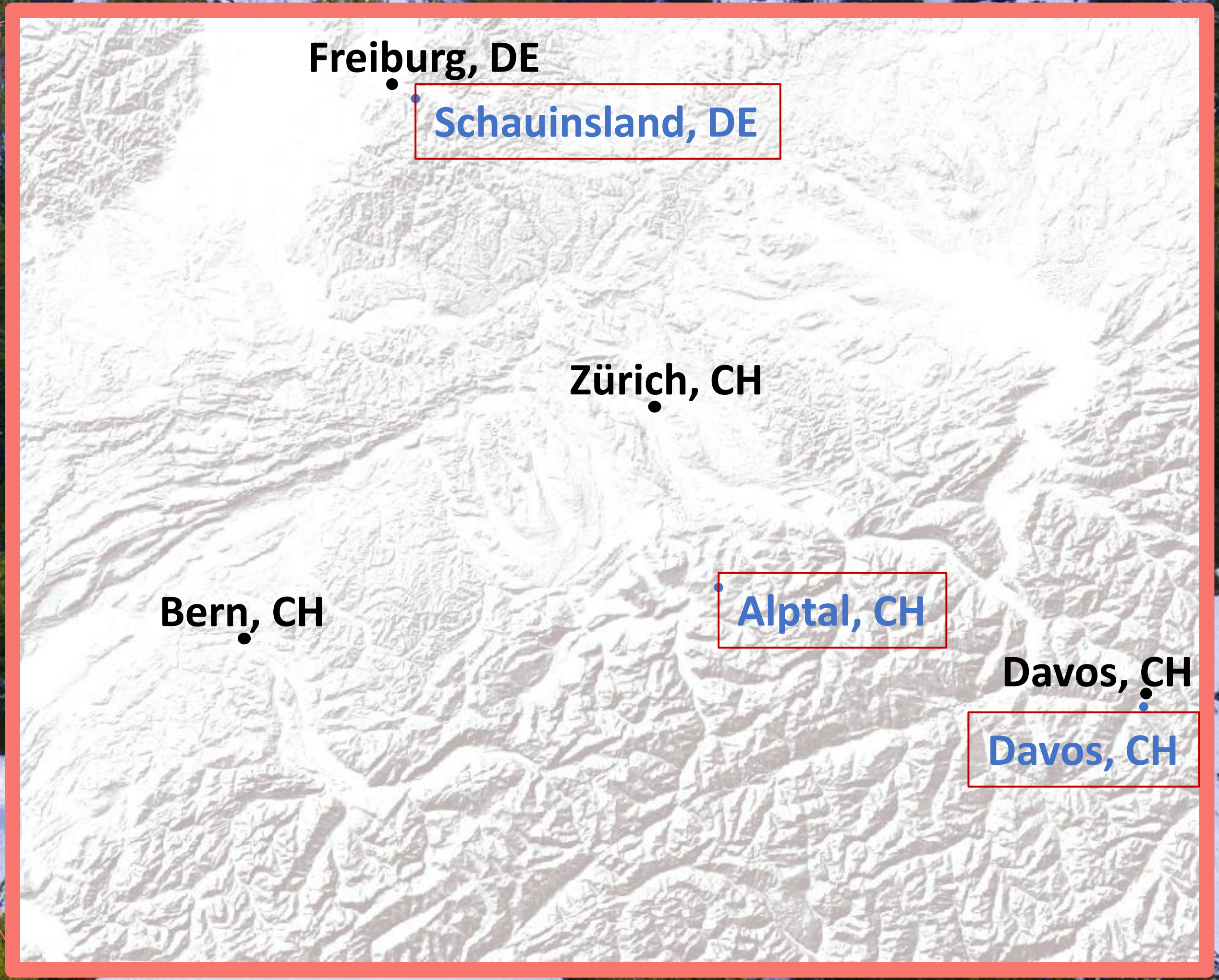

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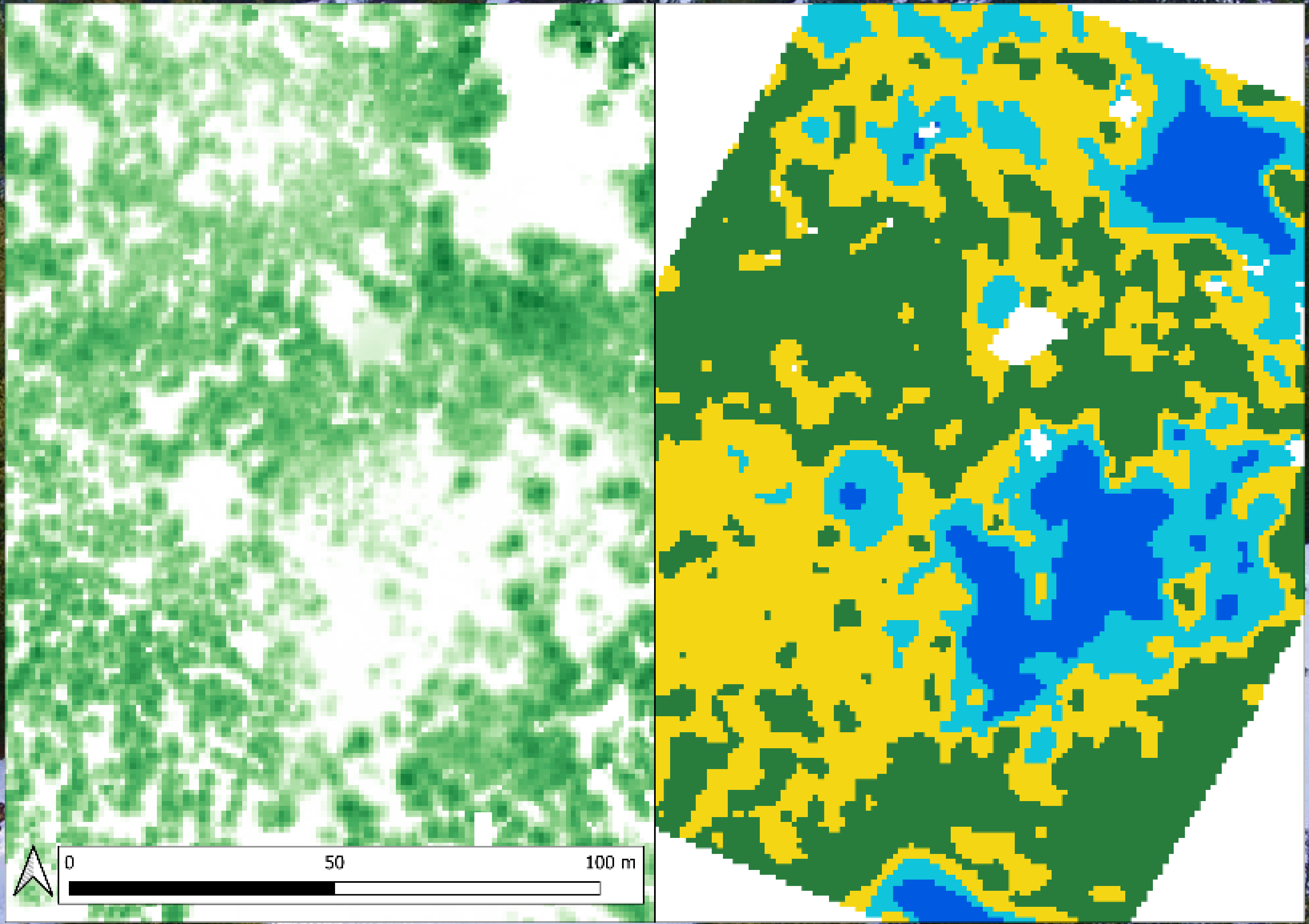
Data	**Koutantou et al (2022)**
Number of Flights	8
Aspect	South
Slope	8°-25°
Elevation	1700 m
Forest Type	Coniferous
Season	2020/2021
Size	0.037 km²



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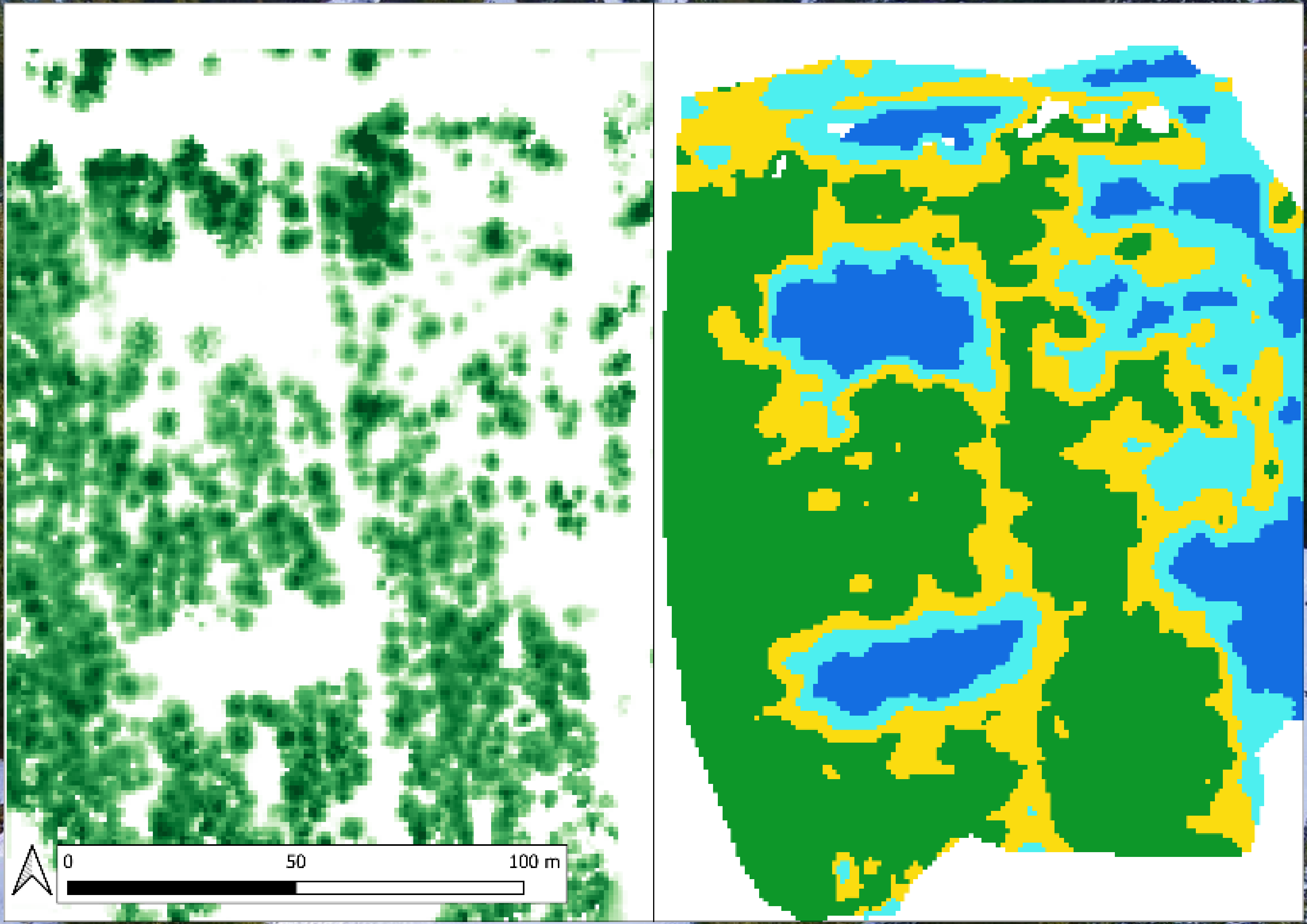
Data	**Koutantou et al (2022)**
Number of Flights	13
Aspect	North
Slope	20°-34°
Elevation	1700 m
Forest Type	Coniferous
Season	2020/2021
Size	0.032 km²



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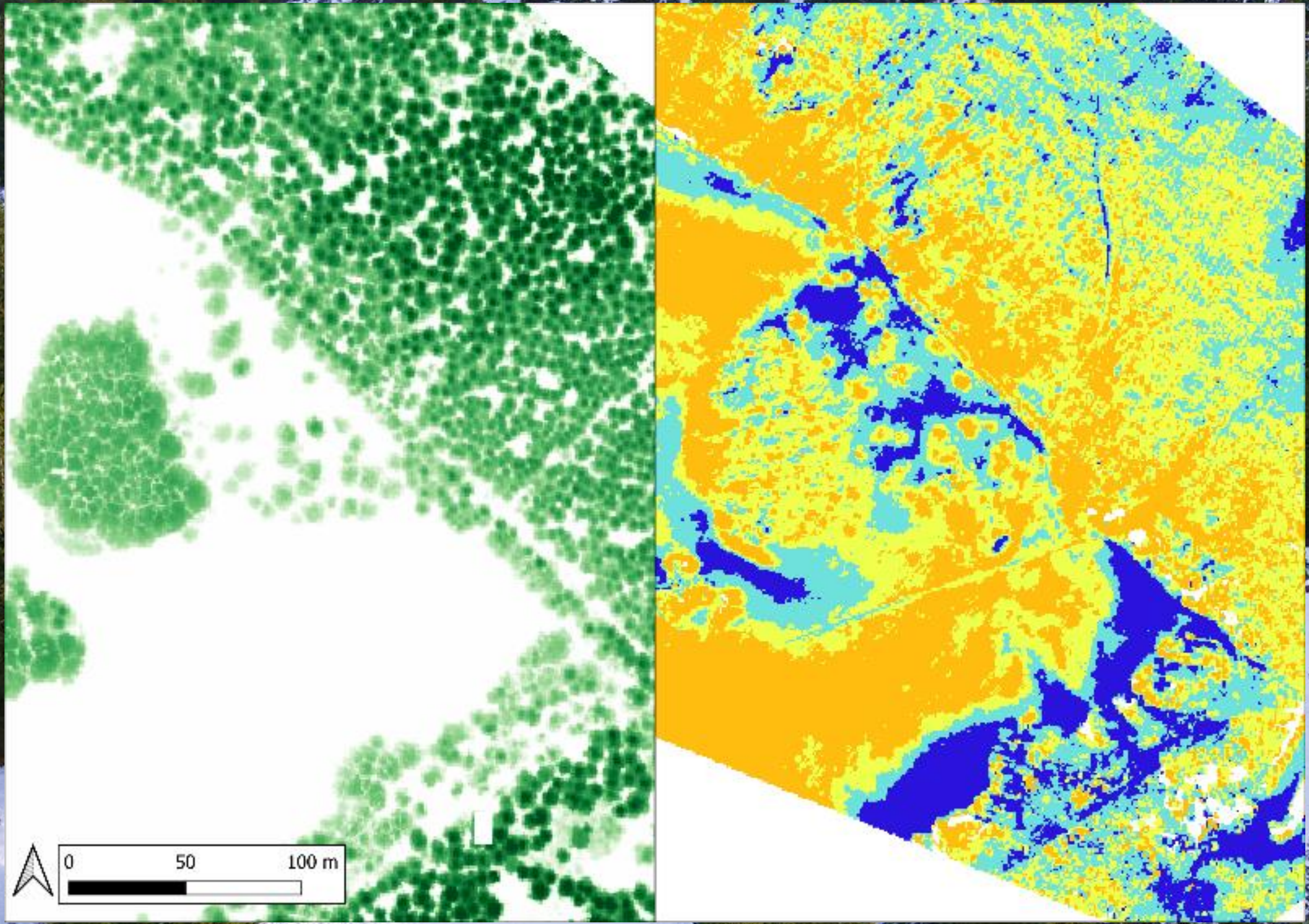
Data	**Geissler et al (unpublished)**
Number of Flights	7
Aspect	All (Summit)
Slope	0°-14°
Elevation	1200 m
Forest Type	Coniferous
Season	2021-2023
Size	0.22 km²



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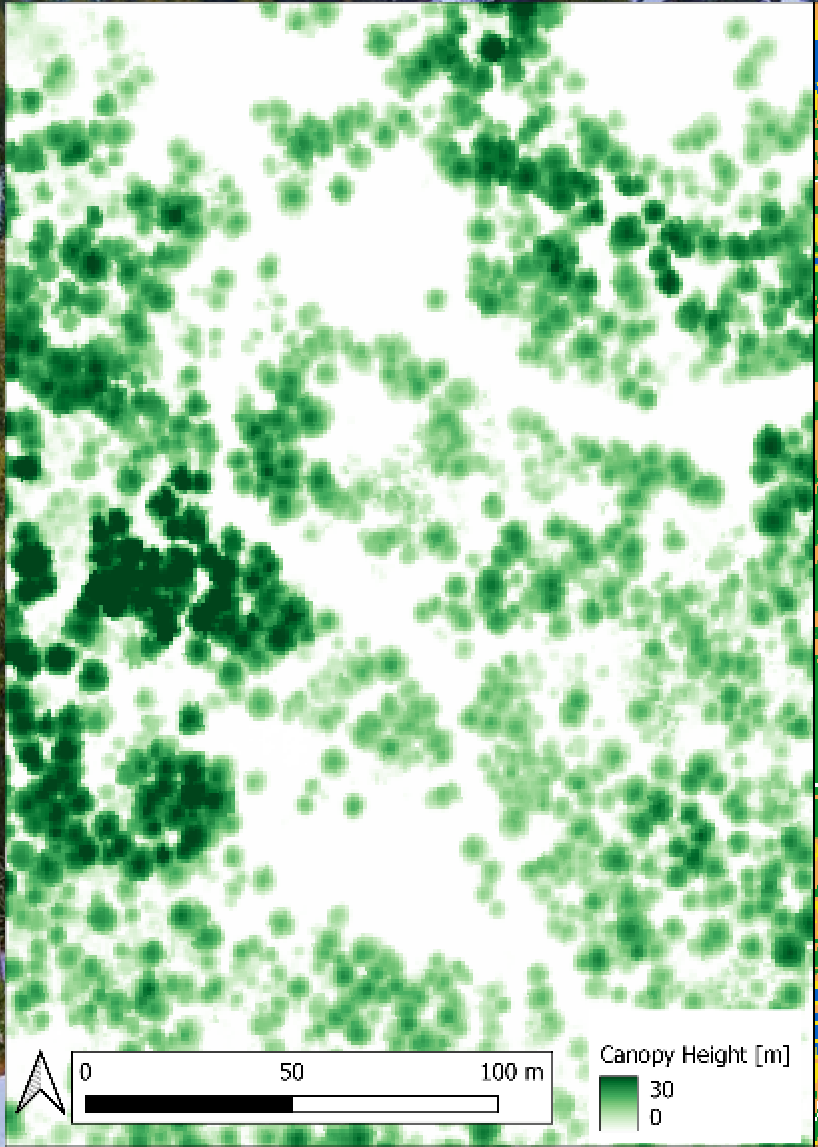
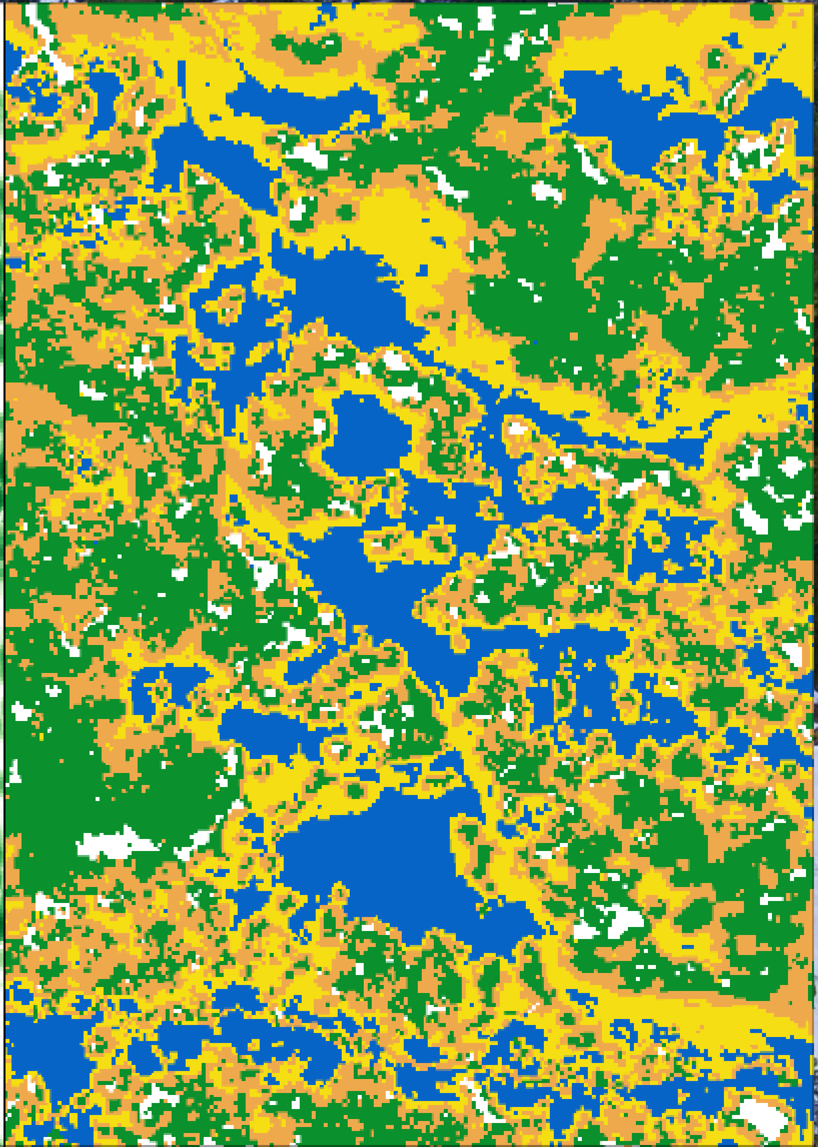
Data	**Geissler et al (2023)**
Number of Flights	12
Aspect	West
Slope	7°-16°
Elevation	1200 m
Forest Type	Coniferous
Season	2021-2023
Size	0.23 km²





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