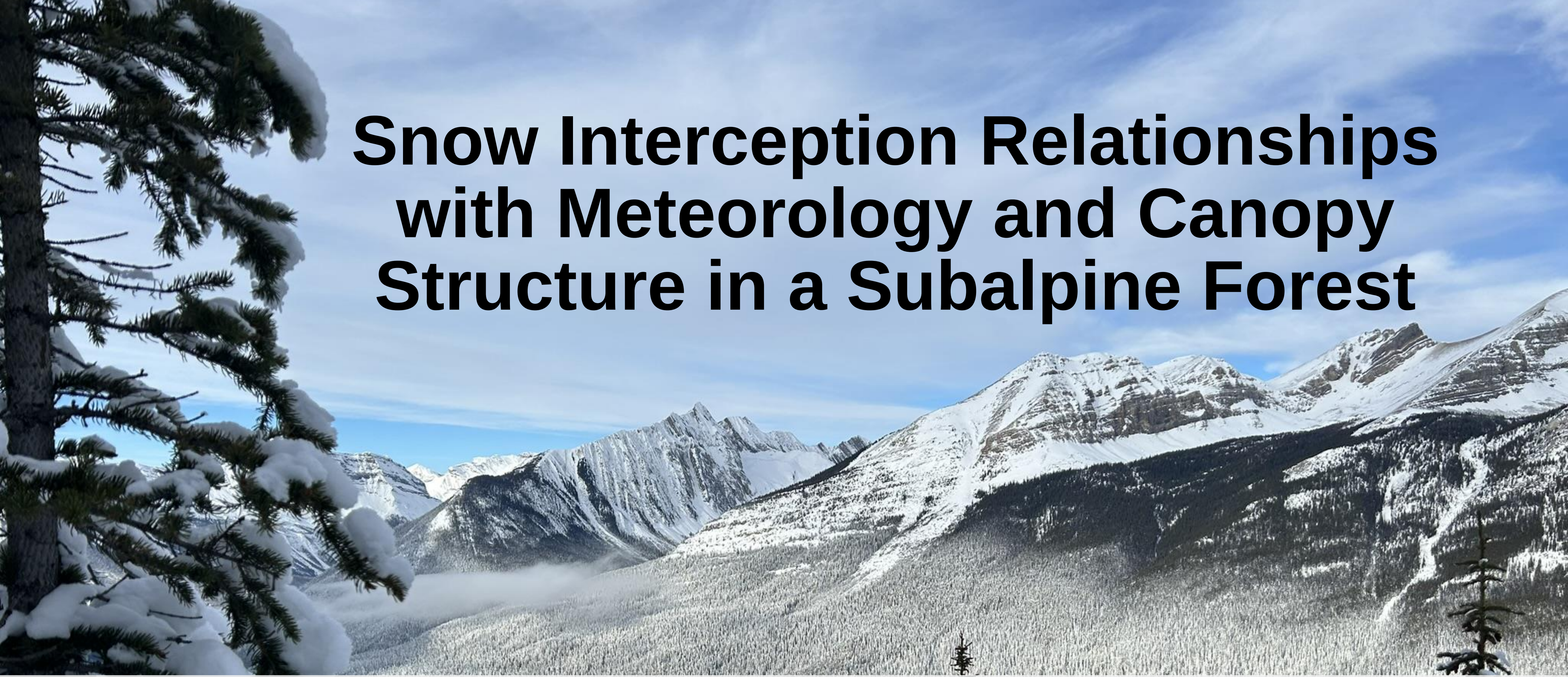

Snow Interception Relationships with Meteorology and Canopy Structure in a Subalpine Forest

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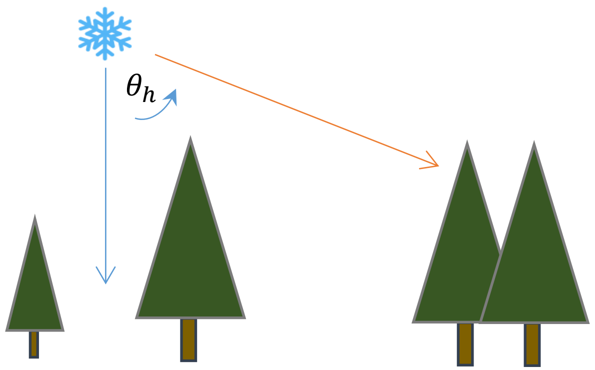
Research Plan

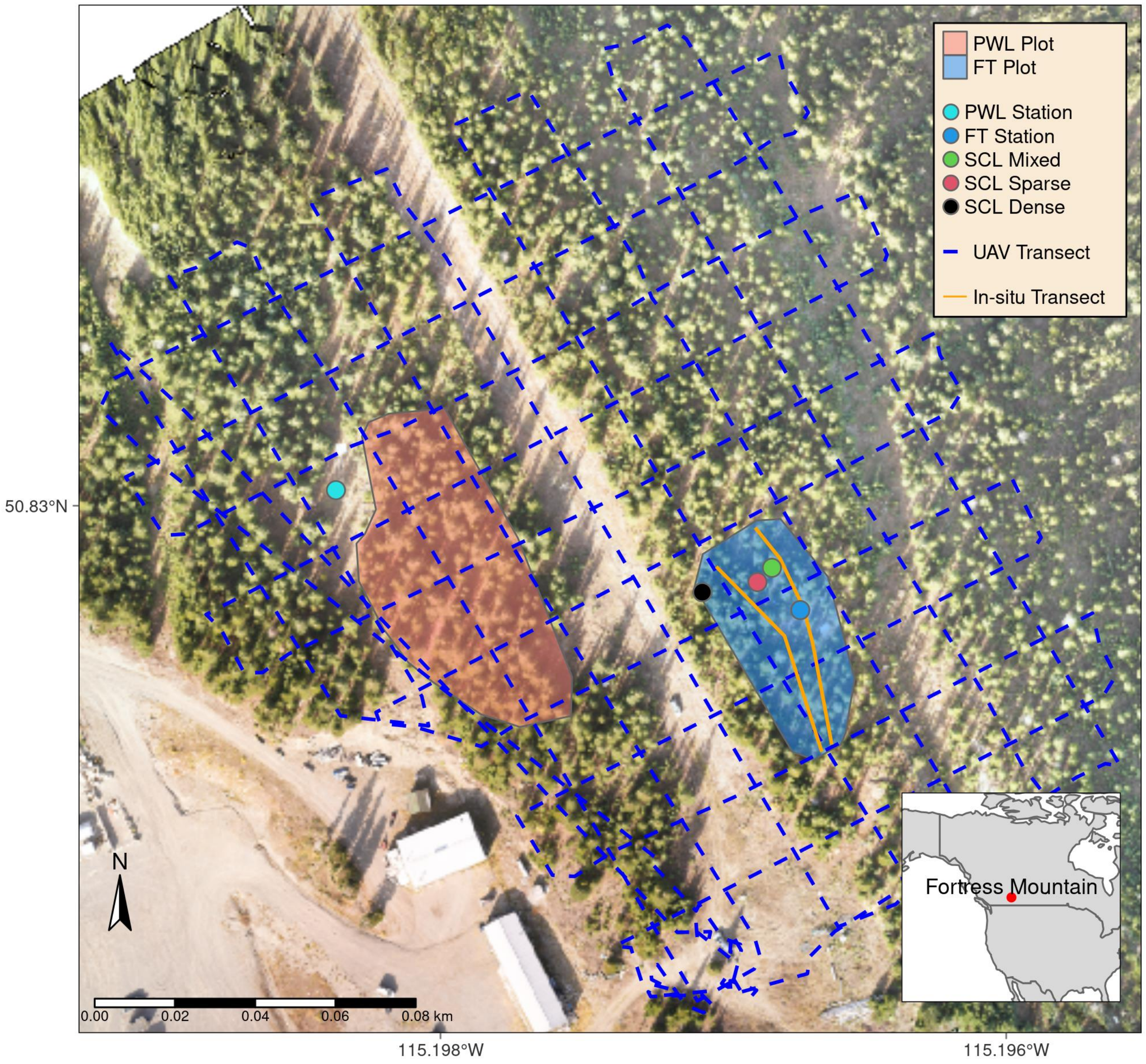


- Objective: To evaluate the theories underlying existing snow interception models using high spatial and temporal resolution measurements of subcanopy snow accumulation
- Research Questions:
  1. Are the existing theories of snow interception supported by in-situ observations?
  2. Is snow interception influenced hydrometeor trajectory angle?
  3. To what extent can these findings inform the development of a new parameterization for snow interception?

Methodology focused on assessing initial snow interception without unloading and other ablation impacts.

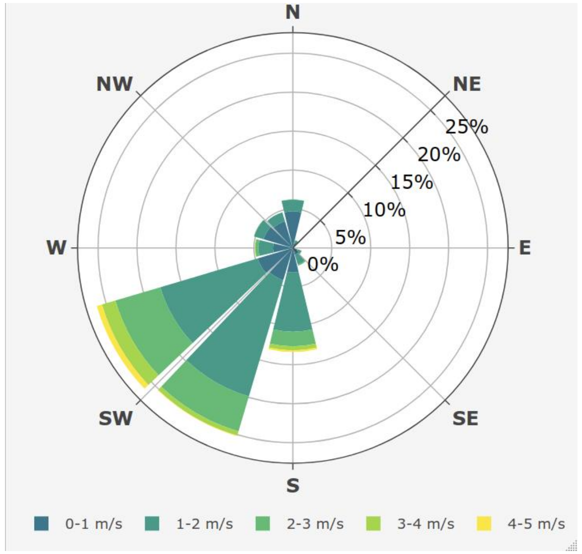
Study Site

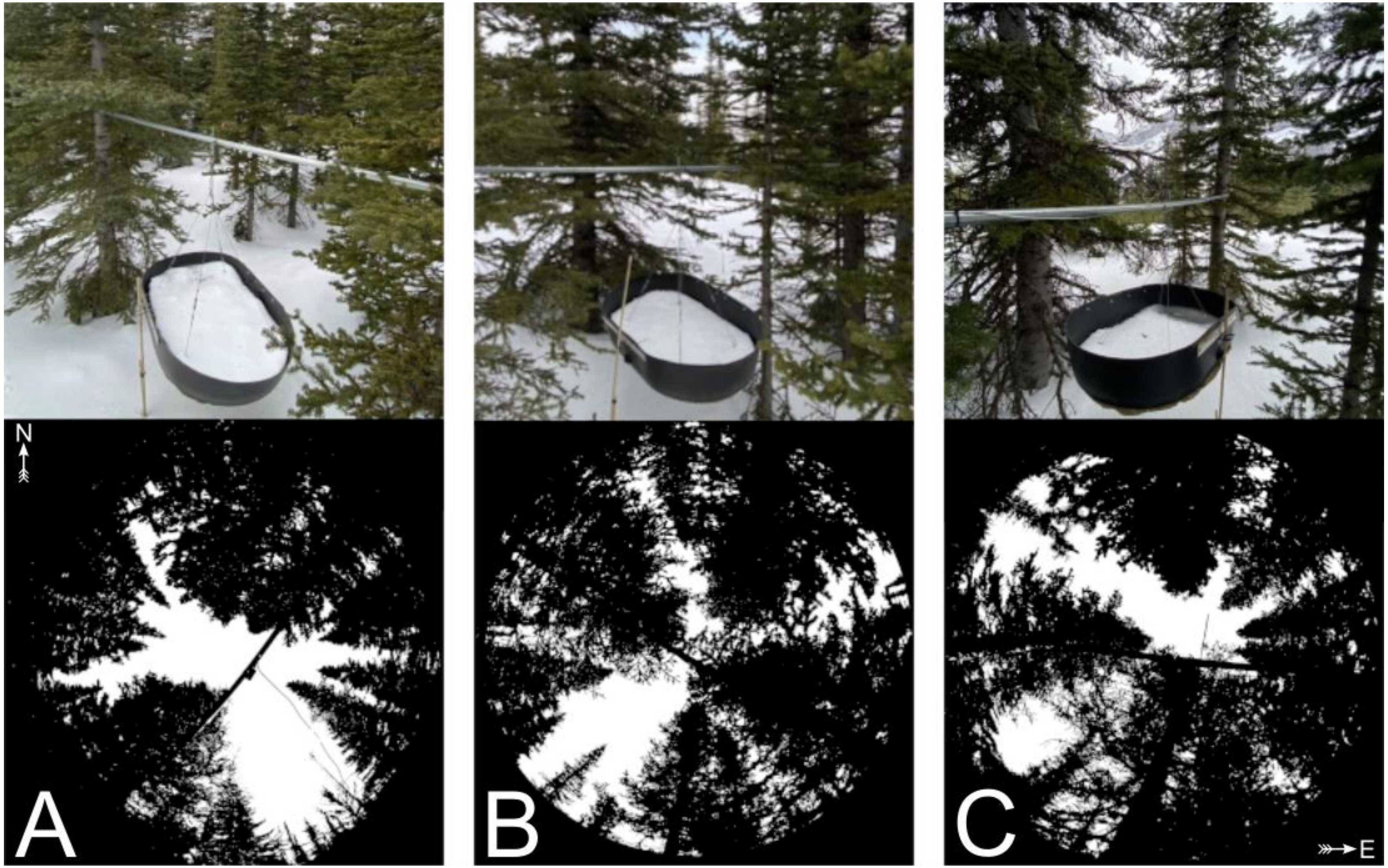
- Fortress Mountain Research Basin, Kananaskis, Alberta, Canada
- Powerline Station (PWL)
  - PWL plot - 2.6 hectares
  - Canopy coverage - 0.5 (-)
  - LAI - 2.07 (-)
  - Mean Tree height - 10.5 m
- Forest Tower Station (FT)
  - FT plot - 1.4 hectares
  - Canopy coverage 0.3 (-)
  - LAI - 1.66 (-)
  - Mean tree height - 7 m
- Tree Species (Langs et al., 2020):
  - 70% Subalpine fir (Abies lasiocarpa)
  - 30% Engelmann spruce (Picea engelmannii)
- 2100 m above sea level



Continuous Throughfall Measurements

Wind speed statistics over observation period





UAV Lidar Subcanopy Snow Measurements

Event Throughfall:

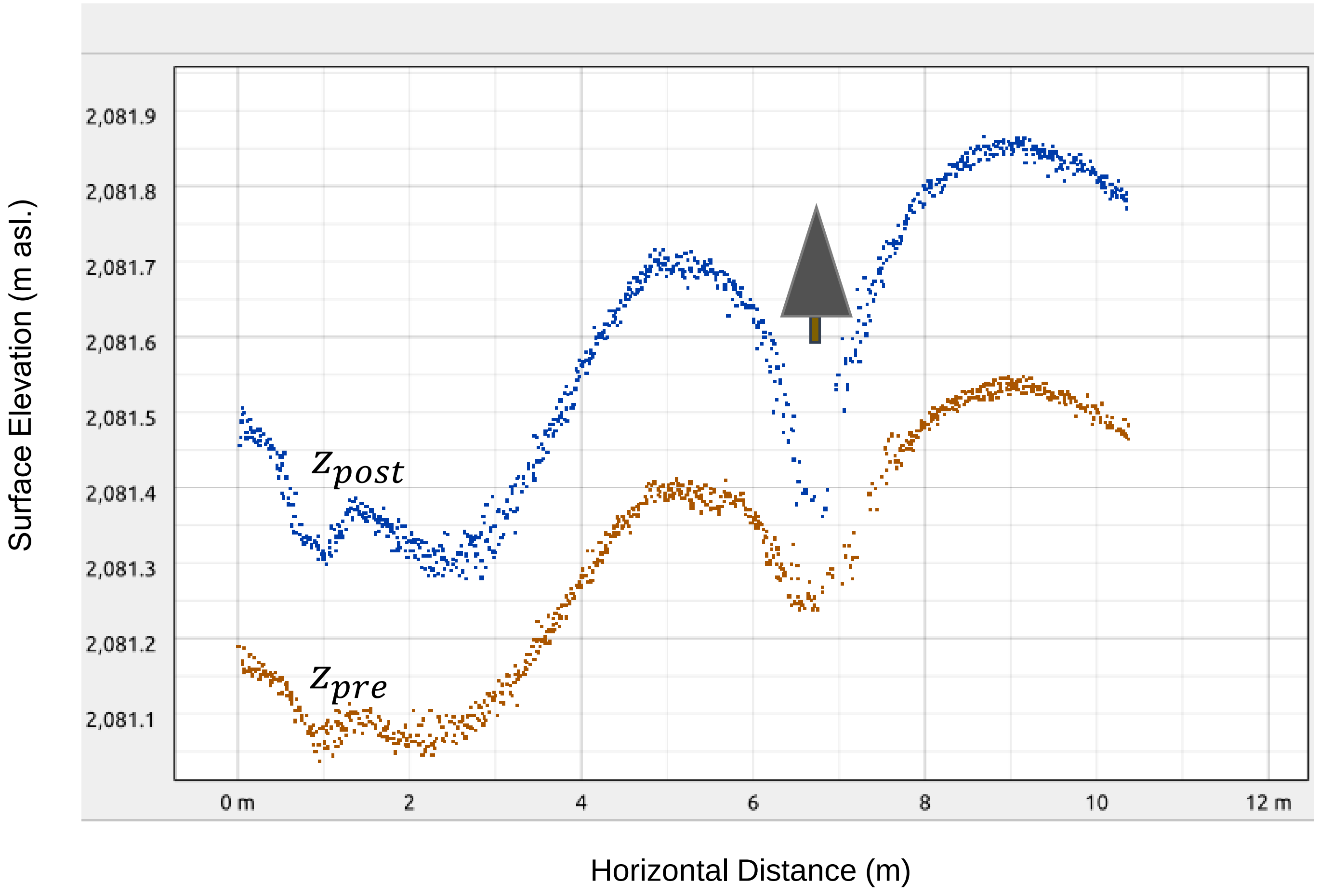
$$\Delta SWE_{tf} = (z_{post} - z_{pre}) \cdot \overline{\rho}$$

Interception Efficiency (-): the fraction of snow intercepted over a discrete time interval

$$\frac{I}{P} = \frac{\Delta SWE_o - \Delta SWE_{tf}}{\Delta SWE_o}$$

Where:

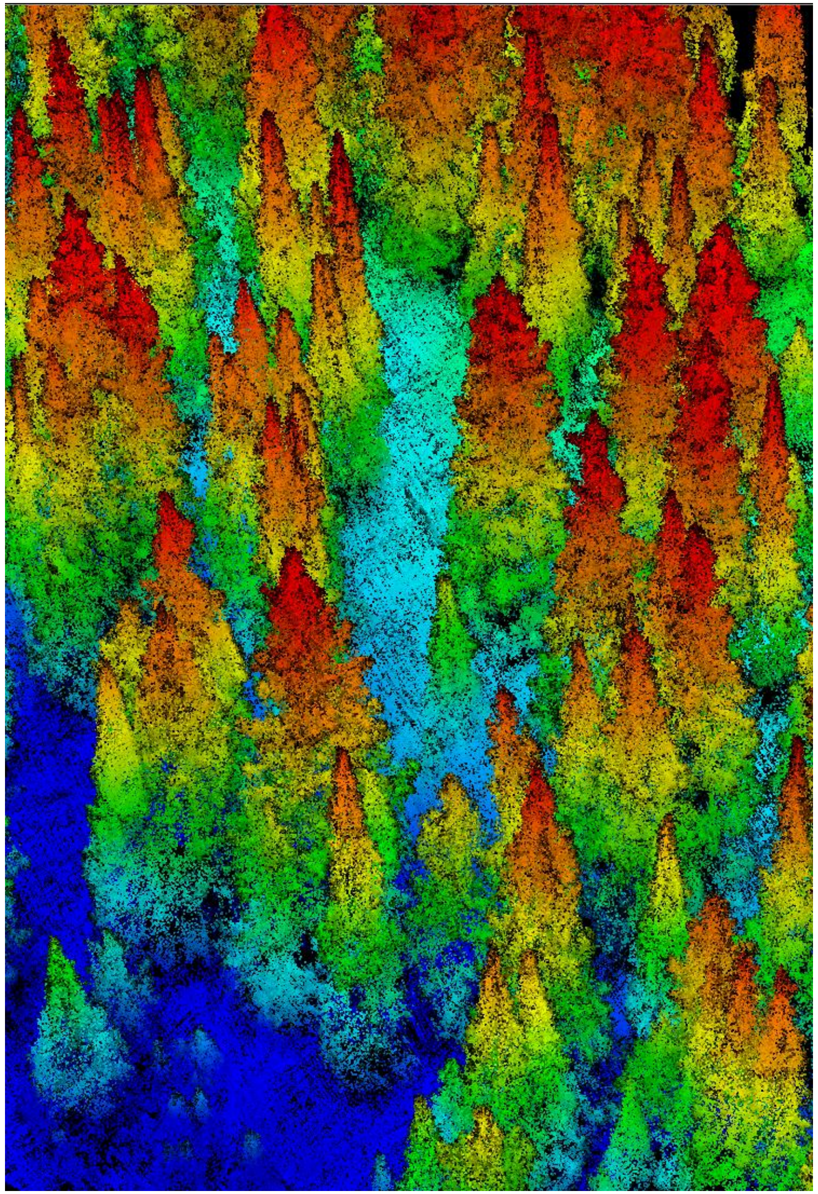
- ΔSWE_o is the change in SWE (kg m^{-2}) to an open clearing over Δt
- ΔSWE_{tf} is the change in subcanopy SWE (kg m^{-2}) over Δt
- $\bar{\rho}$ is the density of fresh snow (kg m^{-3})



Canopy Structure Metrics

Voxel Ray Sampling (VoxRS, Staines & Pomeroy 2023)

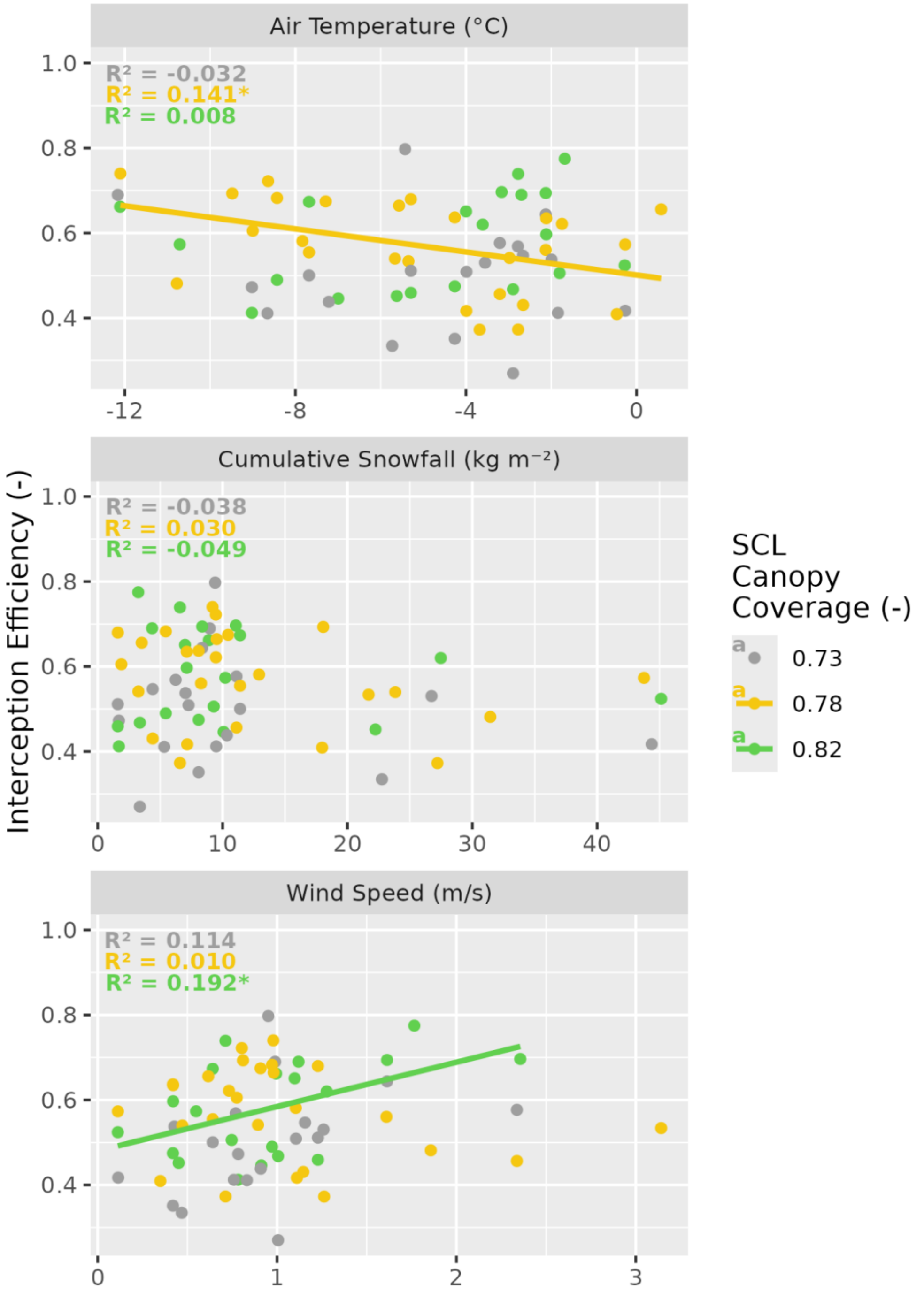
- Leaf contact area ratio (-) = 1 - Radiation Transmittance = Canopy coverage from nadir



VoxRS Code is available at: https://github.com/jstaines/VoxRS

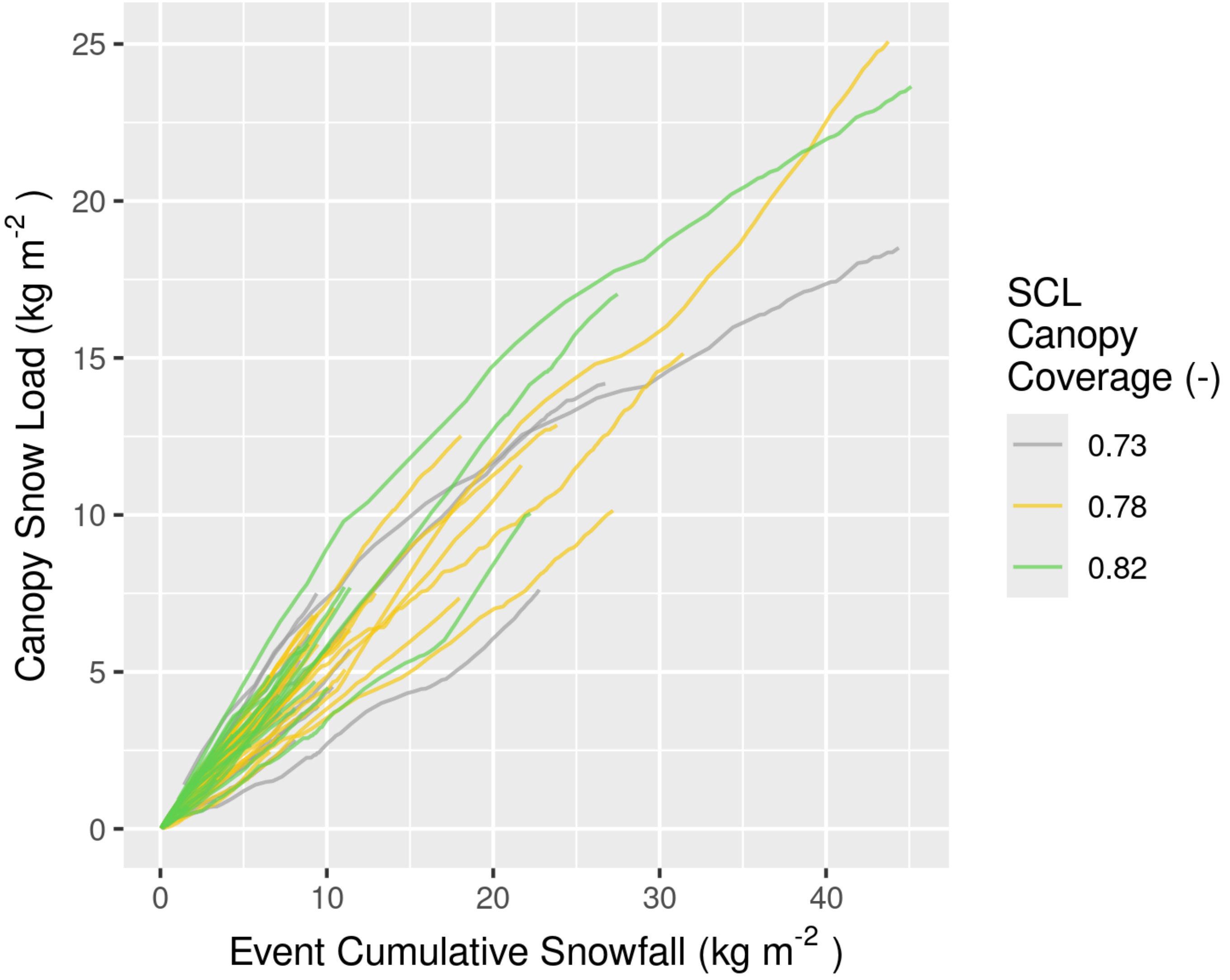
The Influence of Meteorology on Snow Interception

- Mean I/P was estimated for 26 snowfall events
- Little association between mean event air temperature and I/P
- Cumulative event snowfall, P, was not associated with mean event I/P ($p > 0.05$)
- Event mean wind speed was weakly associated with interception efficiency for the sparse ($R^2 = 0.1$, $p > 0.05$) and closed ($R^2 = 0.2$, $p < 0.05$), but not for the mixed canopy ($p > 0.05$)
- The mixed canopy had an opening to the prevailing wind direction resulting in a different association of I/P with wind speed
- Overall weak influence of meteorology and canopy snow load on I/P
- Other factors which may influence remaining scatter:
  - Influence of wind direction changing apparent forest structure
  - Change in cohesion and adhesion of snow to the canopy
  - Eddies and backflows in the canopy influencing hydrometeor trajectory



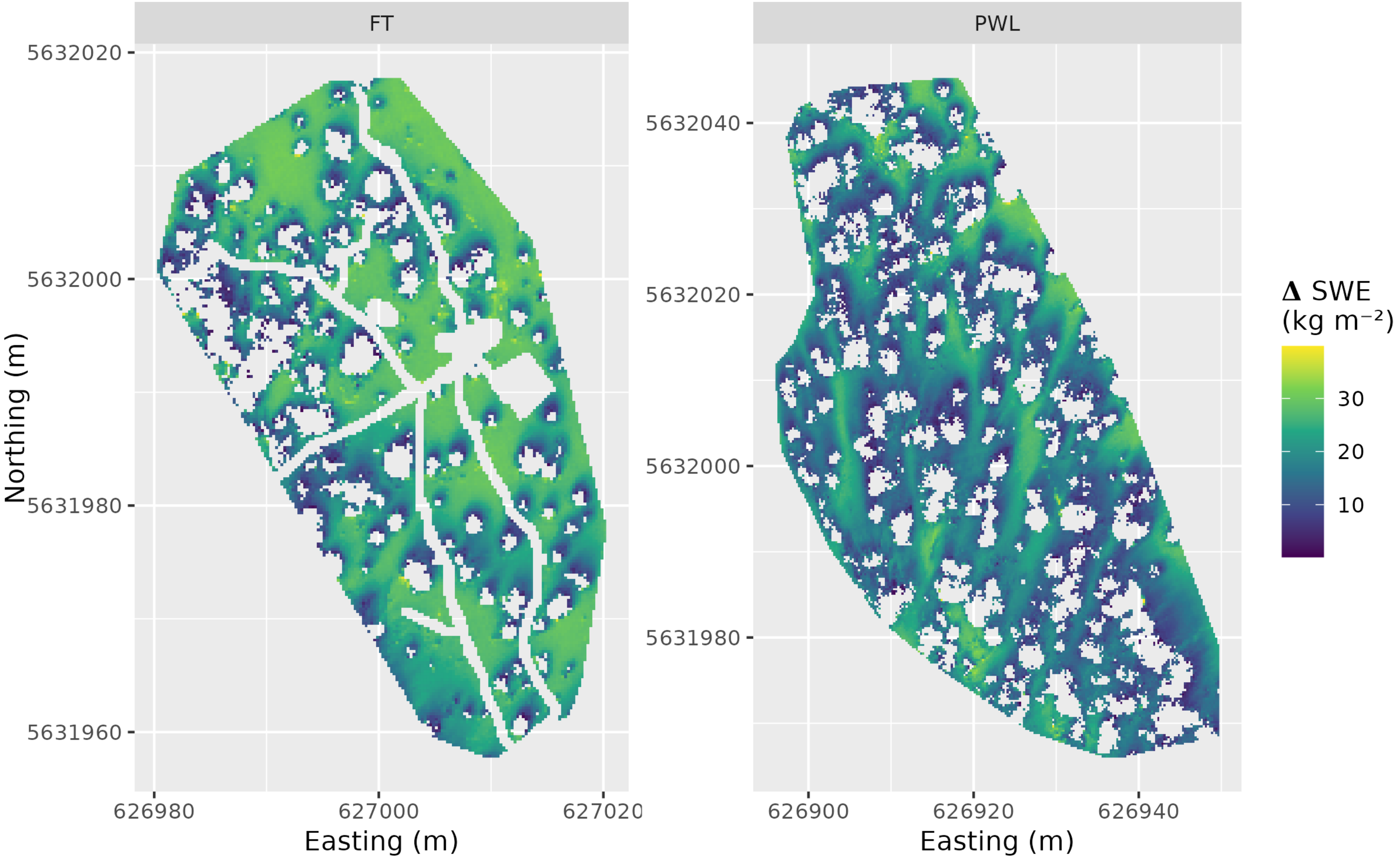
The Influence of Meteorology on Snow Interception

- Canopy snow load calculated from the three lysimeters using a mass balance
- Over these events:
  - Air temperature ranged from -24.5°C to 1°C
  - Wind speed at 4.3 m height ranged from calm to 4.6 m s^{-1} inducing non-vertical snowfall trajectories
- No evidence of a maximum canopy snow load, even for event snowfalls up to 45 kg m^{-2}

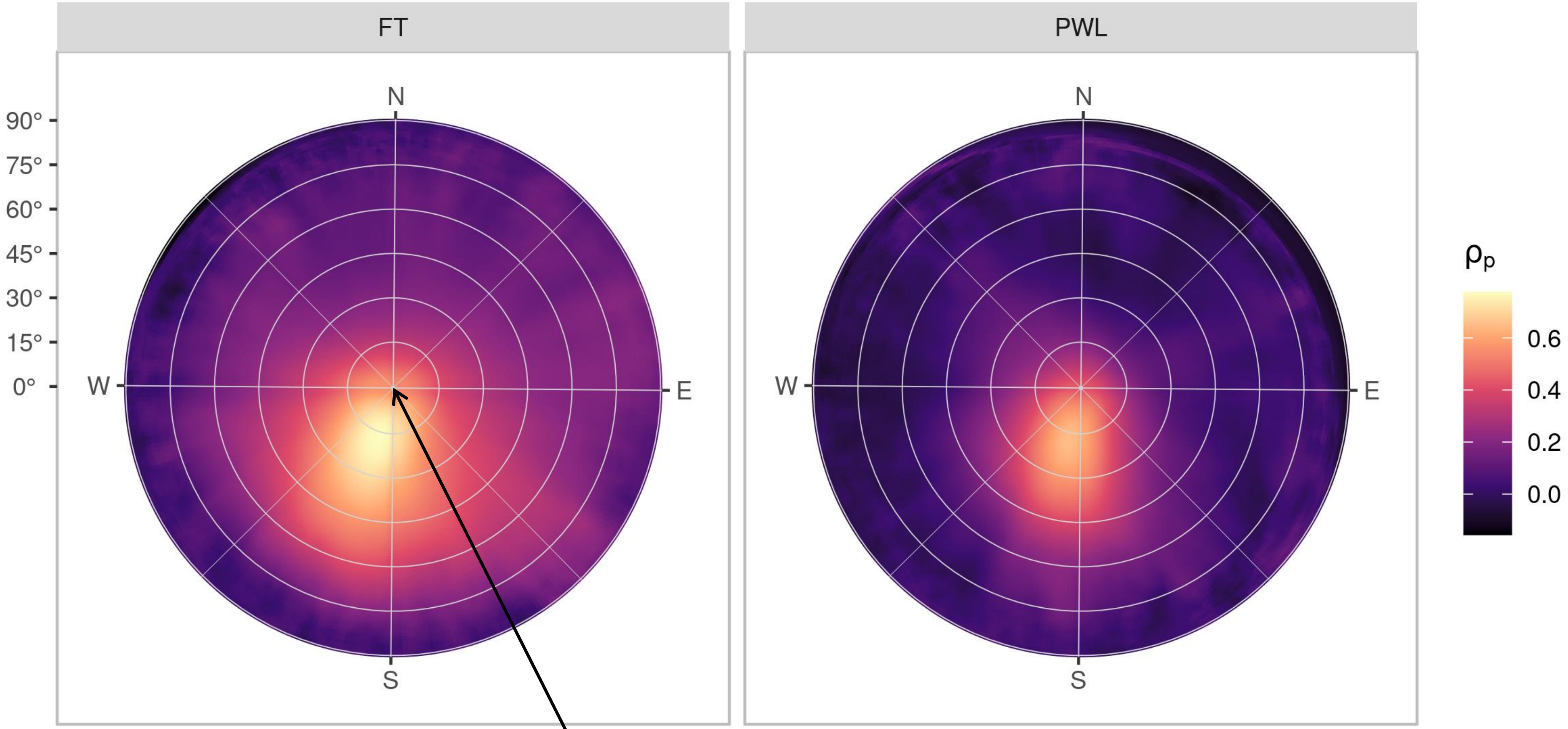


The Influence of Forest Structure on Snow Interception

- 28.7 kg m^{-2} of snowfall over a 24 hr period
- Snowfall coincided with air temperatures around -2.5 °C
- Average wind speed of 1.3 m s^{-1} from the south
- Reduced SWE on lee side of individual trees

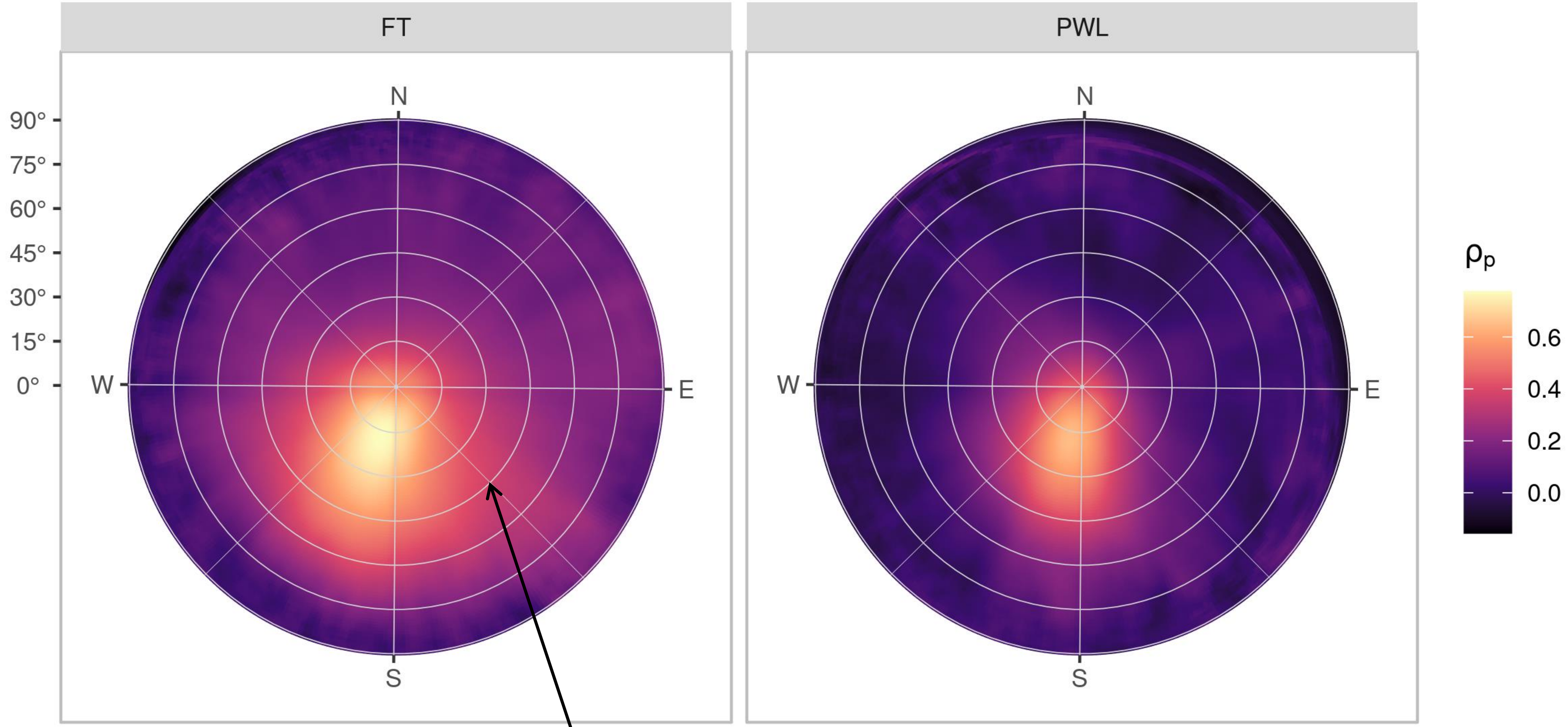


The Influence of Forest Structure on Snow Interception



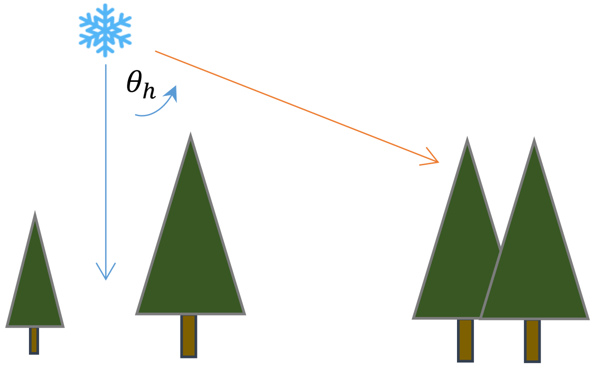
ρ_p = Pearson Correlation(Leaf Contact Area [0,0], I/P)

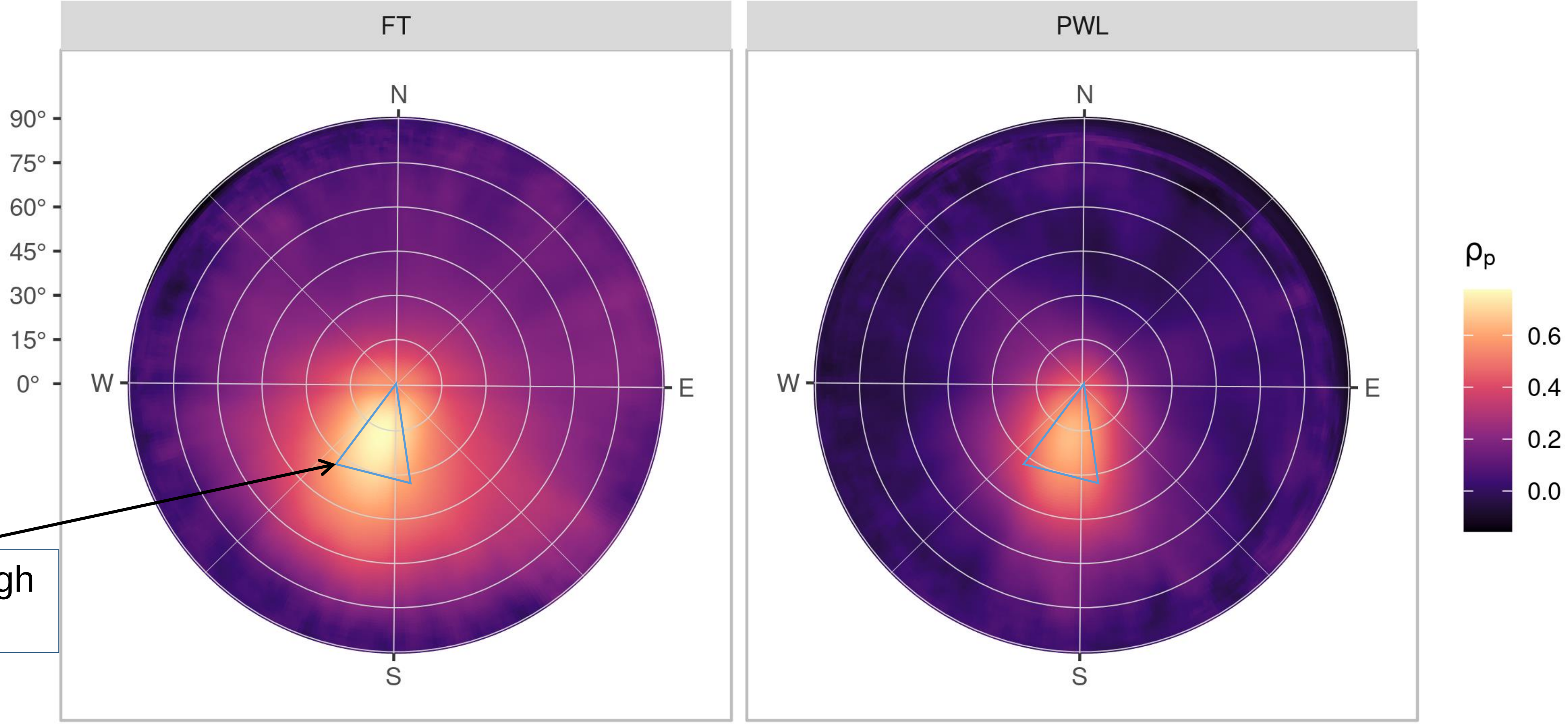
The Influence of Forest Structure on Snow Interception



ρ_p = Pearson Correlation(Leaf Contact Area [45°,135°], I/P)

The Influence of Forest Structure on Snow Interception

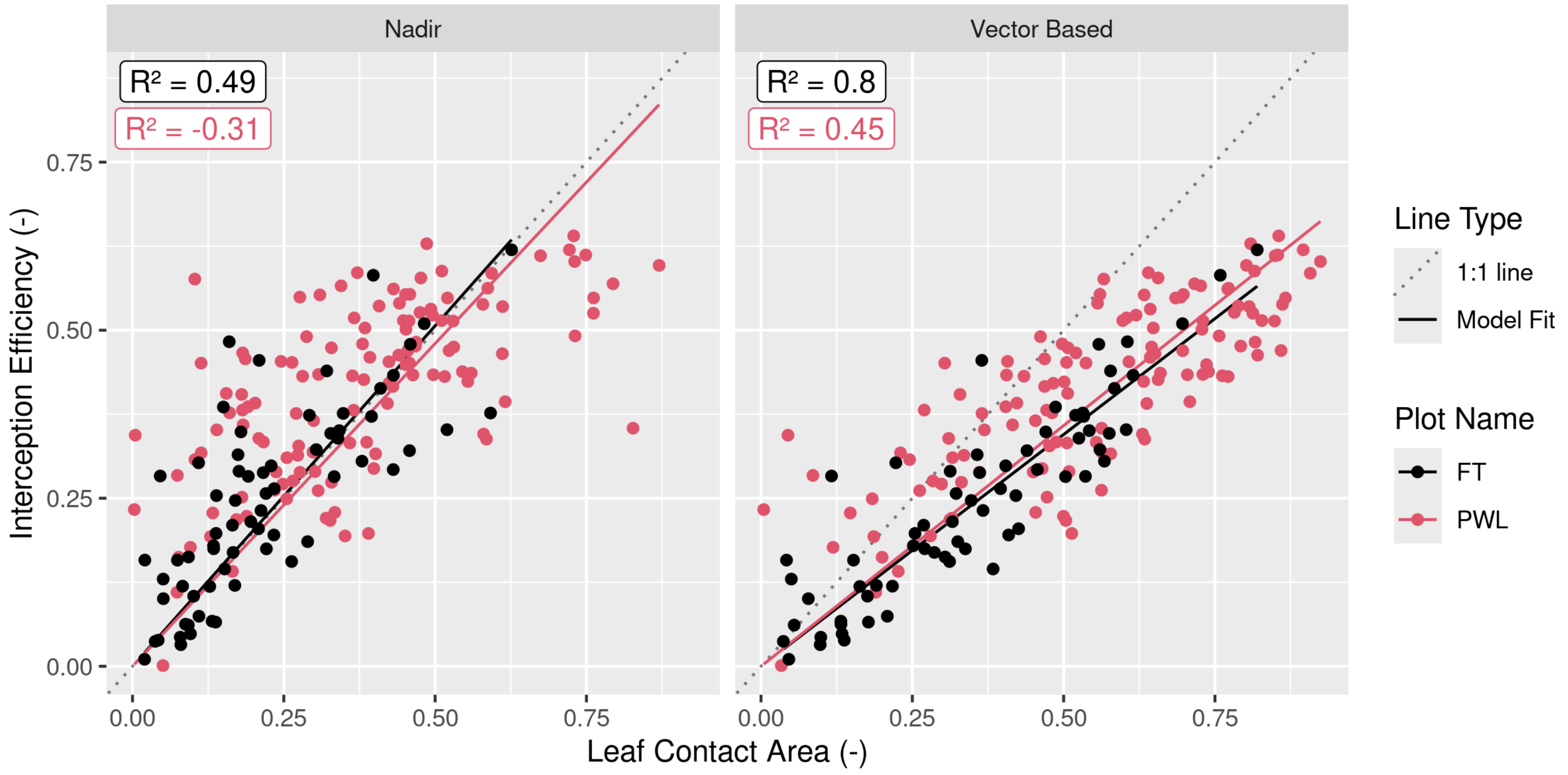




Zone of high correlation

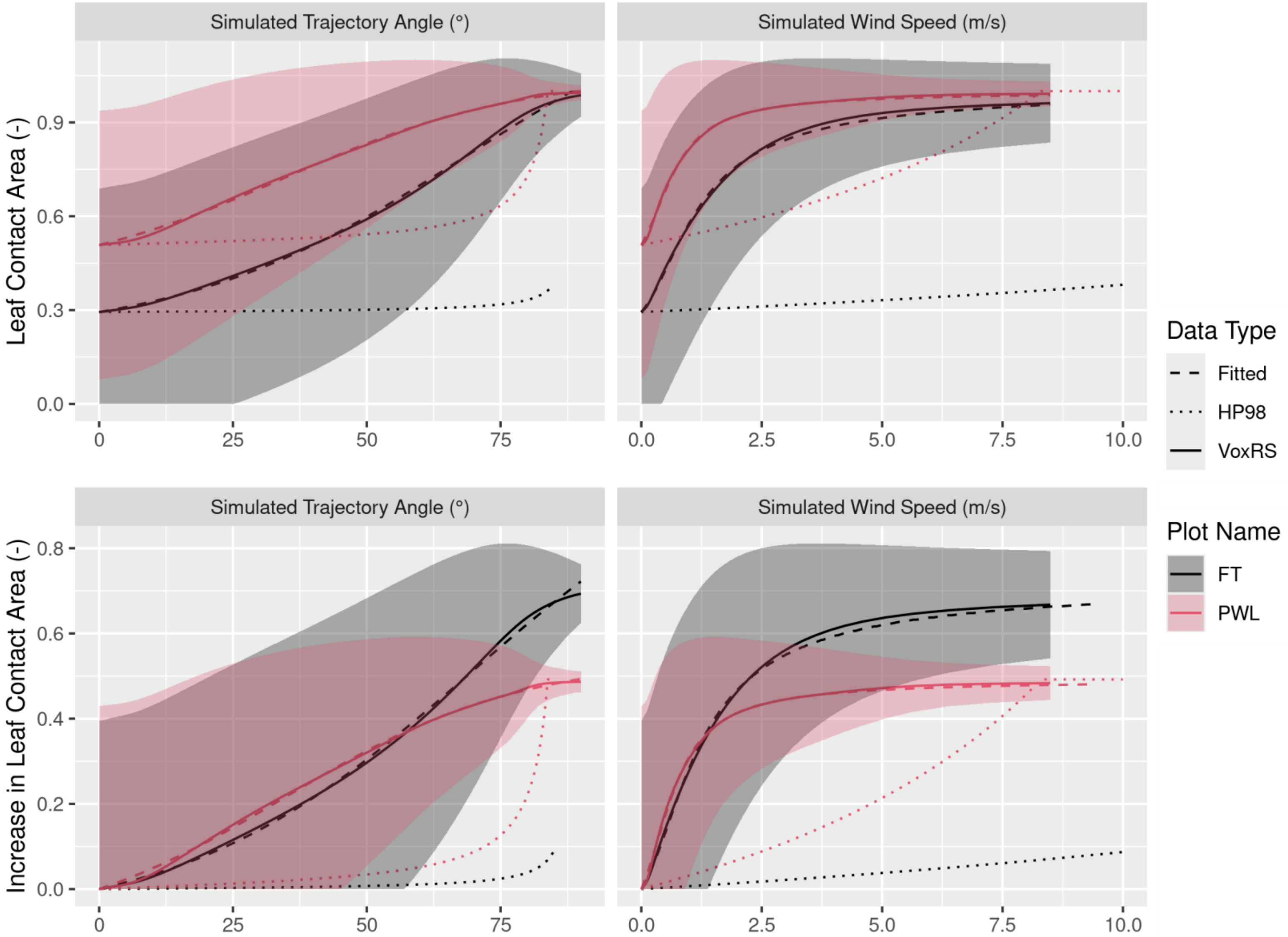
The Influence of Forest Structure on Snow Interception

- Leaf contact area, adjusted for trajectory angle (Vector Based) was strongly associated with I/P ($R^2 = 0.8$)
- The Nadir model had a lower R^2 for both plots
- A slope of ~0.7 was observed for the Vector Based model
- Vector based leaf contact area is a potential useful predictor of initial I/P (before unloading and other ablation)



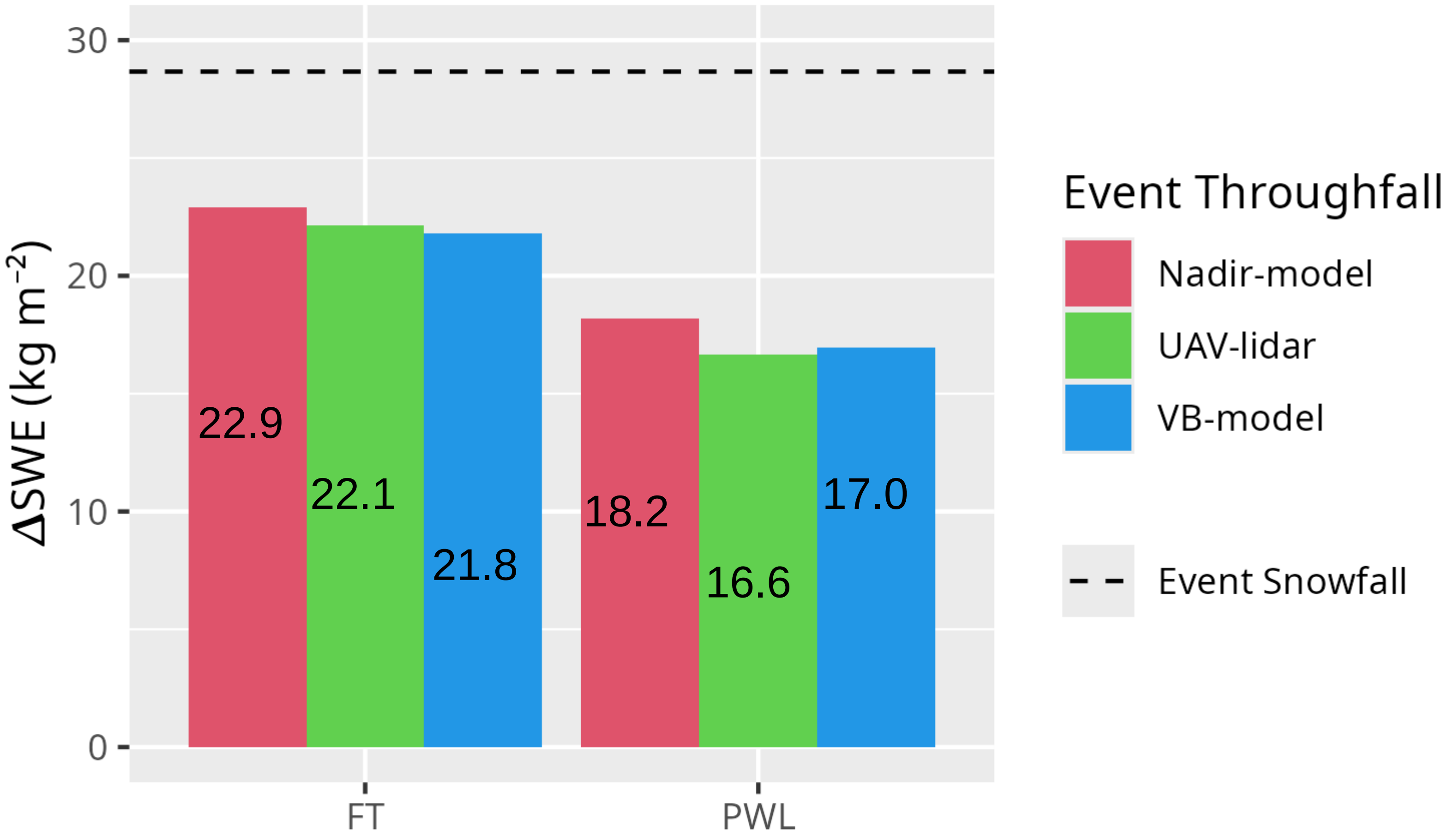
The Influence of Trajectory Angle and Forest Structure on Interception

- Leaf contact area increased substantially with trajectory angle and corresponding simulated wind speed
- For a 1 m s^{-1} wind speed and terminal fall velocity of 0.9 m s^{-1}, C_p increases by 60% for PWL and 100% for FT
- Existing theory (HP98) proposed but failed to represent this relationship



Throughfall Model Performance

- The Vector Based (VB) model had improved performance compared to the Nadir model for both plots
- The mean bias for the VB model is:
  - 0.3 kg m^{-2} and -0.3 kg m^{-2} for FT and PWL
- The mean bias for the Nadir model is:
  - -0.8 kg m^{-2} and -1.6 kg m^{-2} for FT and PWL



Conclusions

- Forest structure was found to be the primary factor governing subcanopy snow accumulation
- Evidence for a maximum canopy snow load was not found for our initial canopy snow interception measurements (no ablation)
- No association was found between canopy snow load or air temperature with I/P at the point scale
- Wind speed was found to increase interception efficiency through an associated change in hydrometeor trajectory angle which also shifts the snow-leaf contact area
- A new parameterization is proposed that calculates snow interception before ablation as a function of snowfall and leaf contact area
- This new model showed good performance for one event at this study site but further work is needed to validate this model in a range of meteorologies, climates and forest canopies

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Appendix

New Interception Model

- C_p is the snow-leaf contact area (-)
- C_c is the canopy coverage (from nadir)
- θ_h is the hydrometeor trajectory angle
- α is an interception efficiency constant
- C_{inc} is the increase in leaf contact area from C_c
- Logistic function variables:
  - C_{inc}^{max} is the maximum value of C_{inc}
  - θ_0 is the x-value of the sigmoid midpoint
  - k is the logistic growth rate or steepness of the curve

$$\frac{I}{P} = C_p(C_c, \theta_h) \cdot \alpha$$

$$C_p = C_c + C_{inc}(\theta_h)$$

$$C_{inc} = \left(\frac{C_{inc}^{max}}{1 + e^{\left(\frac{\theta_0 - \theta_h}{\mathrm{k}}\right)}} - \frac{C_{inc}^{max}}{1 + e^{\left(\frac{\theta_0}{\mathrm{k}}\right)}} \right)$$

Change in Canopy Snow Load

The change in canopy snow load over time, $\frac{dL}{dt}$ (kg m^{-2}), may be represented as:

$$\frac{dL}{dt} = q_{sf} - q_{tf}(L) - q_{unld}(L) - q_{drip}(L) - q_{wind}^{veg}(L) - q_{sub}^{veg}(L) \qquad (4)$$

If ablative processes are negligible, Equation 4 can be simplified to:

$$\frac{dL}{dt} = q_{sf} - q_{tf}(L) \qquad (5)$$

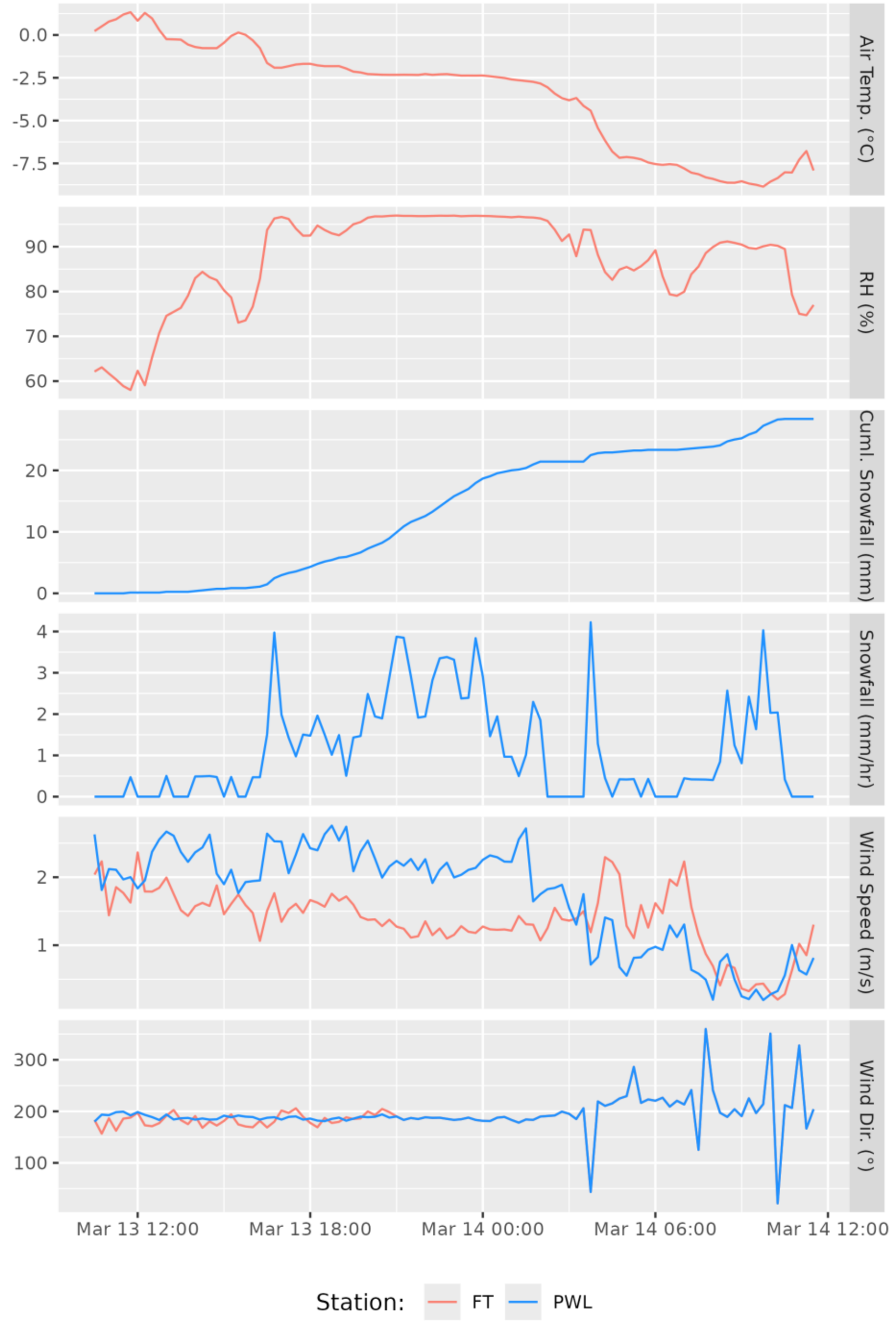
Over a discrete time interval, Δt, the change in canopy snow load, ΔL (kg m^{-2}) may be calculated as:

$$\frac{\Delta L}{\Delta t} = \overline{q_{sf}} - \overline{q_{tf}(L)} = \Delta SWE_o - \Delta SWE_{tf} \qquad (6)$$

where $\overline{q_{sf}}$ and $\overline{q_{tf}(L)}$ are the average snowfall and throughfall rate over Δt. ΔSWE_o is the change in SWE to the open (kg m^{-2}).

Results

- Results from a snowfall event:
  - Start: March 13, 2024 10:00 am
  - End: March 14, 2024 11:00 am
- Event Meteorology:
  - 1.4 m/s wind speed
  - 188° wind direction
  - 0.9 m/s hydrometeor velocity
  - -3.5 °C air temperature



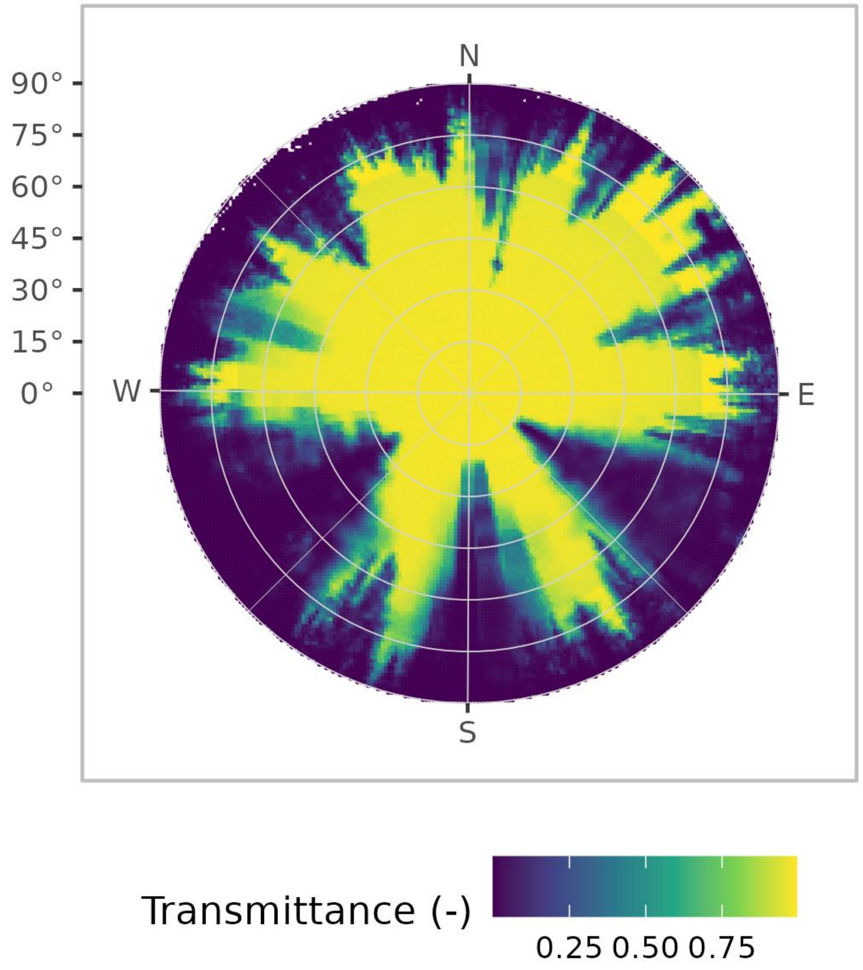
Methods: Aerial LiDAR

- Aerial LiDAR was flown over the study site to measure snow depth and characterise the canopy structure
- Four LiDAR surveys were flown before and after snowfall events on January 26, 2023 and March 13, 2023
- A point cloud of ~2000 x,y,z coordinates were collected per square metre for each survey
- Point clouds were processed using **RiProcess POSPac**, **LASTools and BayesMap**
- LiDAR snow depth was validated and bias corrected using in-situ ruler measurements

Methods: Canopy Metrics

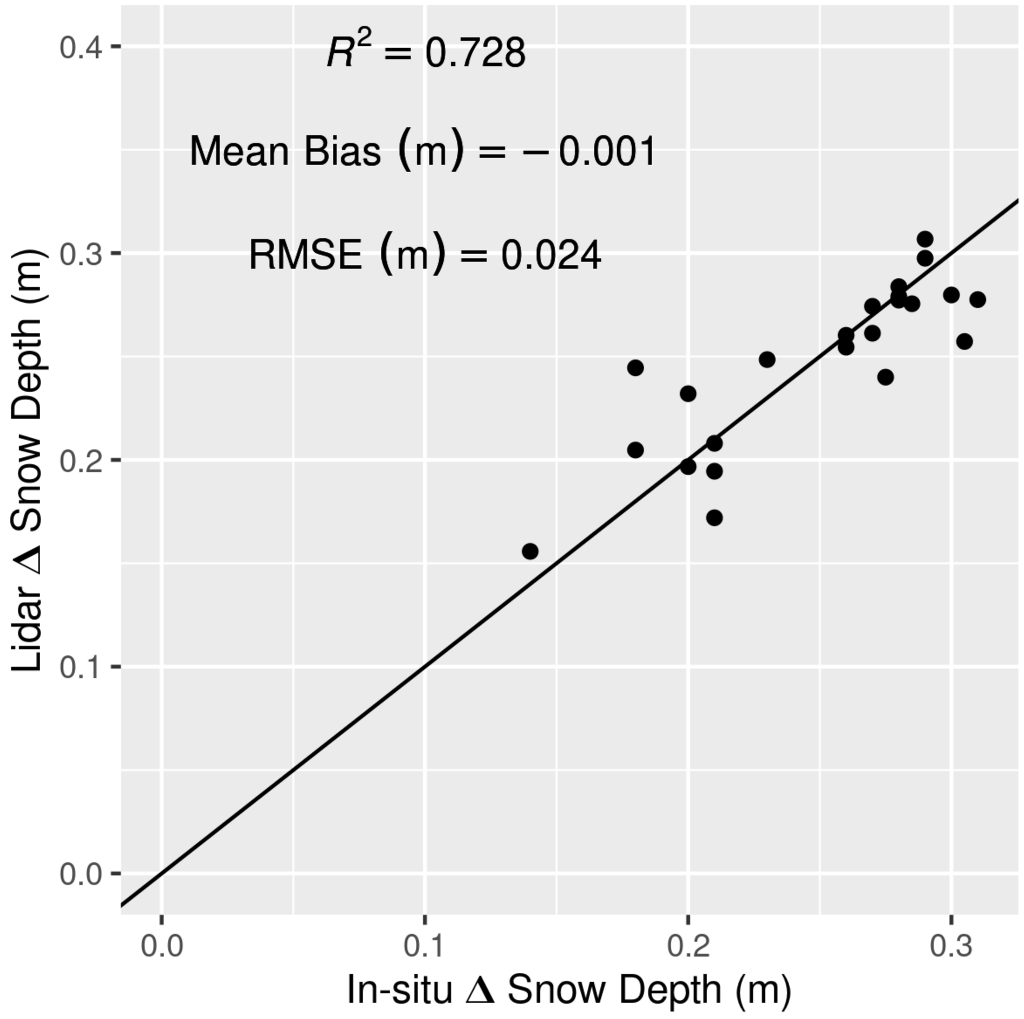
Voxel Ray Sampling (VoxRS, Staines & Pomeroy 2023)

- Canopy Contact Number (-)
- Radiation Transmittance *(-)*
- Leaf contact area ratio (-)
  - 1 - Radiation Transmittance
  - equal to canopy coverage for Nadir
- Run for snow-off and snow-on conditions for two snowfall events (4 surveys in total)



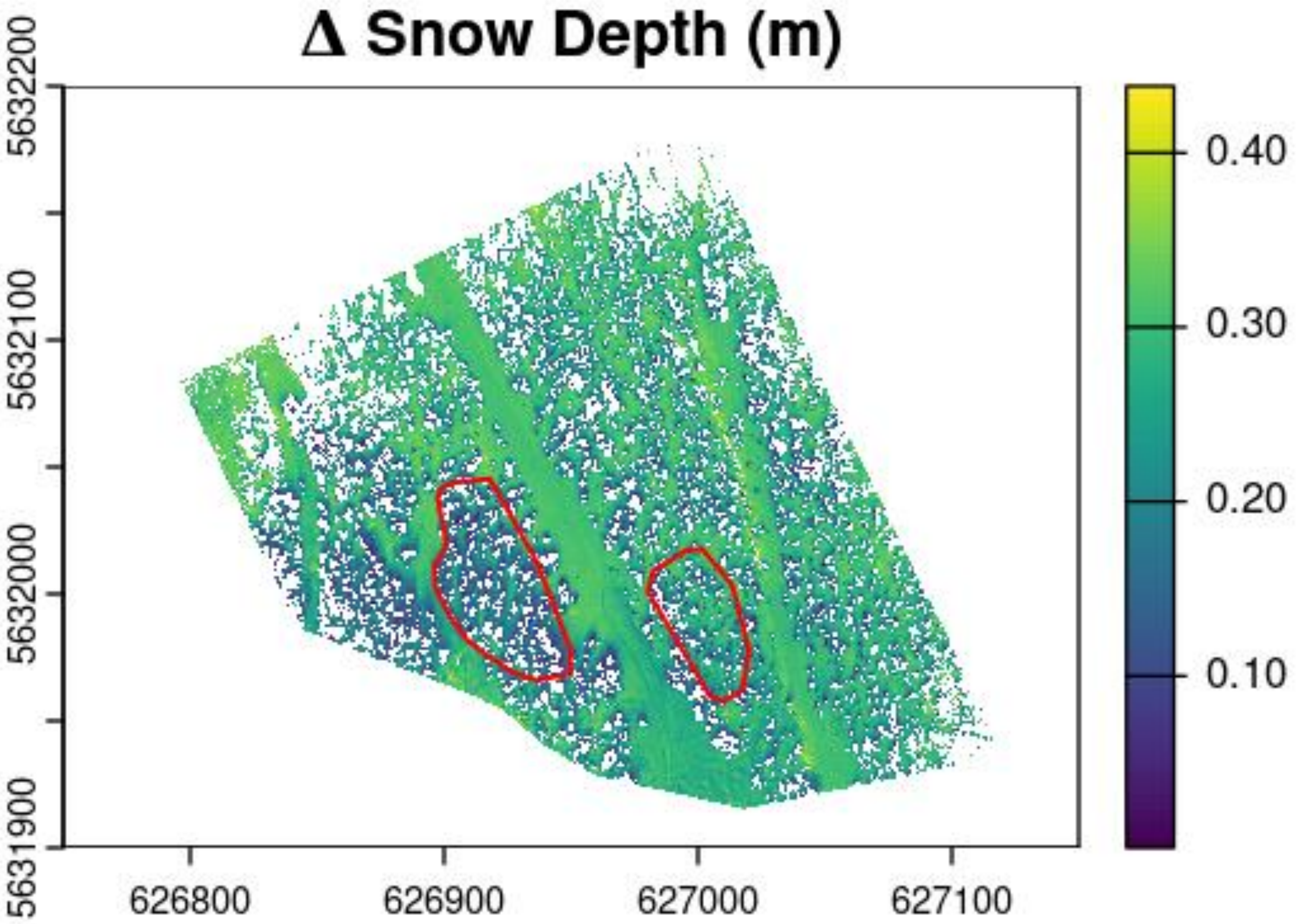
UAV Snow Measurements

- UAV-lidar **Δ** snow depth aligned well with in-situ measurements



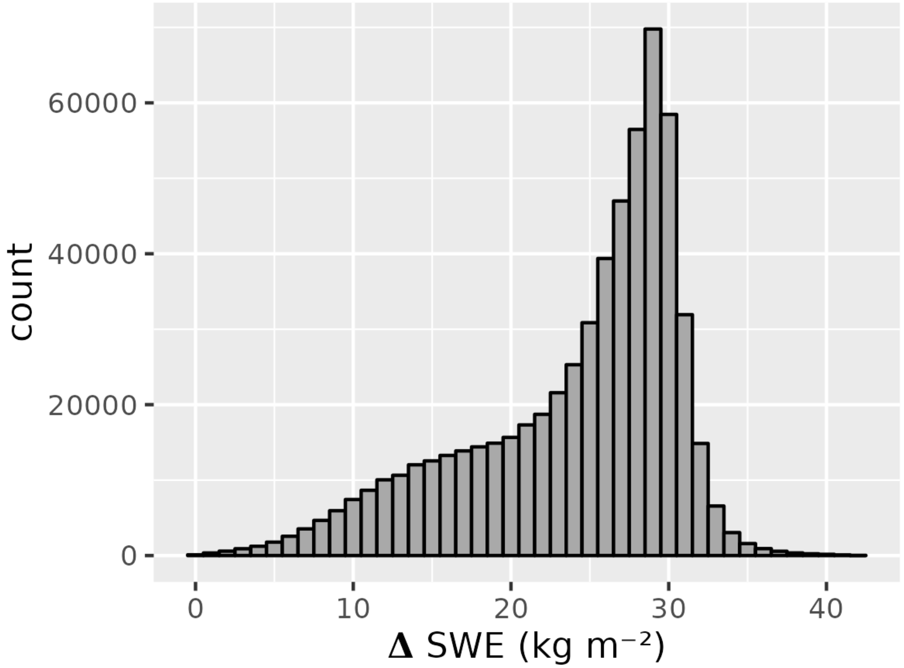
UAV Snow Measurements

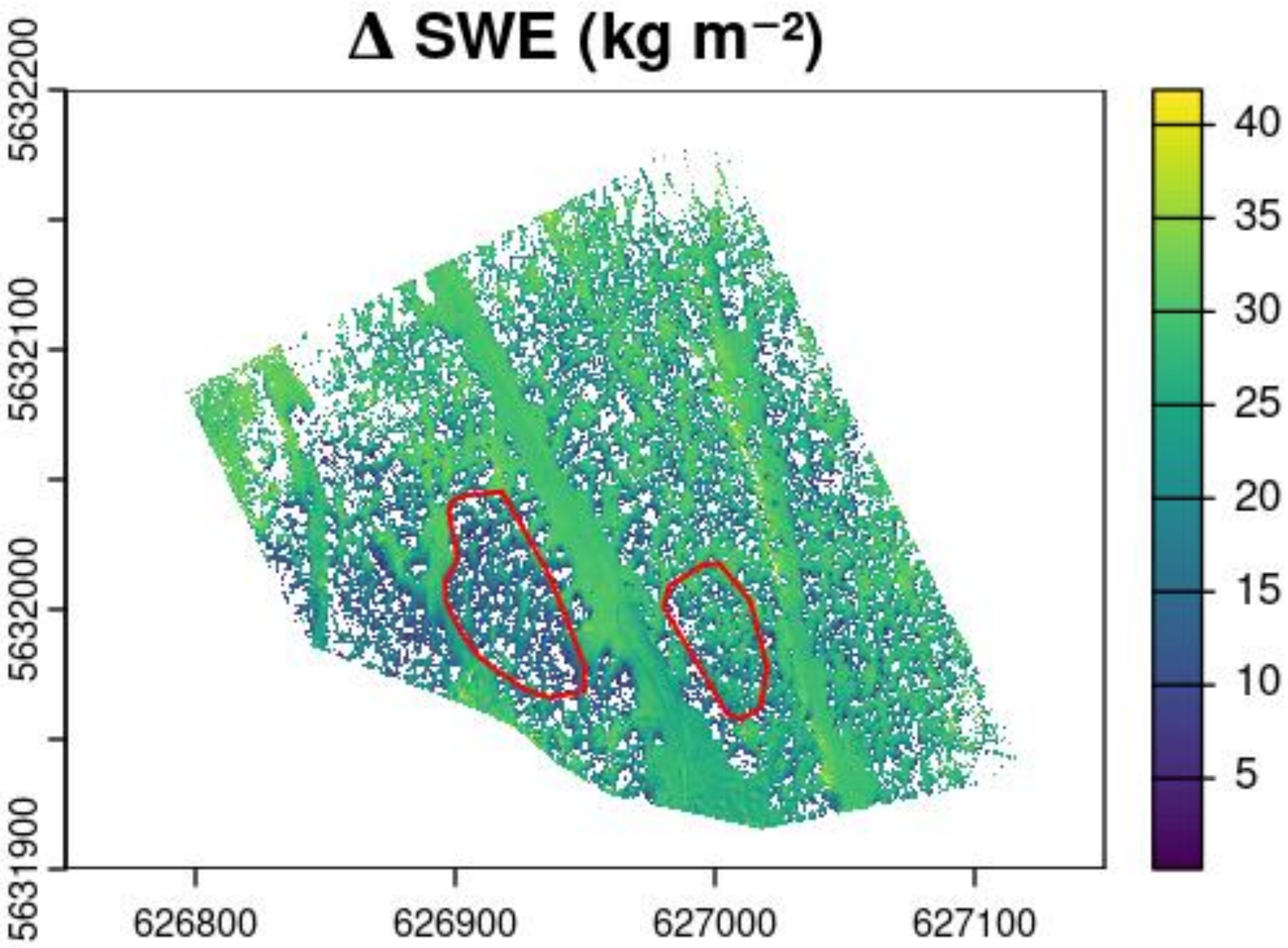
- UAV-lidar **Δ** snow depth aligned well with in-situ measurements
- Resulted in **Δ** snow depth at a 5 cm resolution across the study site (resampled to 25 cm)
- With the exception of dense canopy (white areas)



UAV Snow Measurements

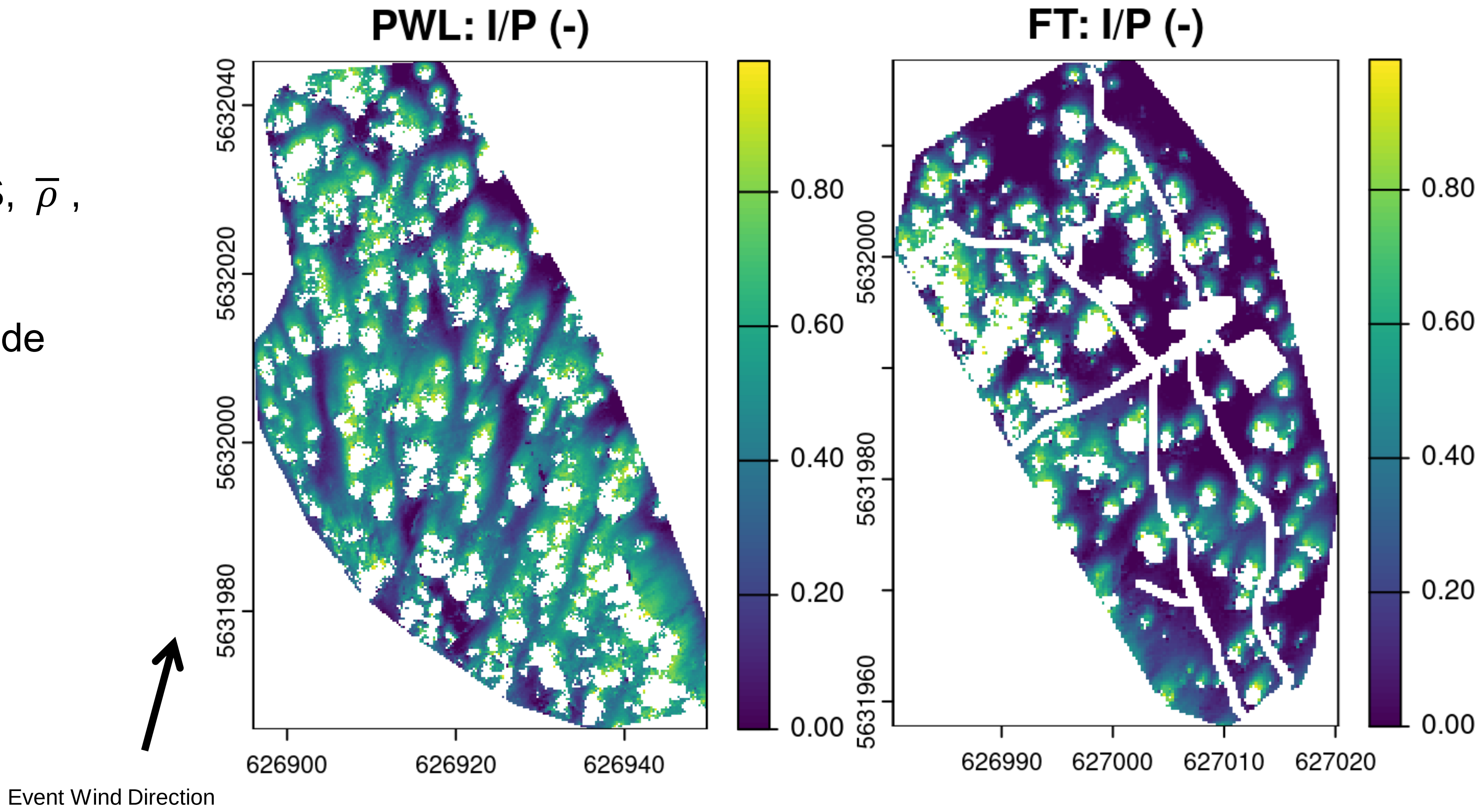
- **Δ**SWE calculated using in-situ fresh snow density ($\overline{\rho}$) provided throughfall measurements



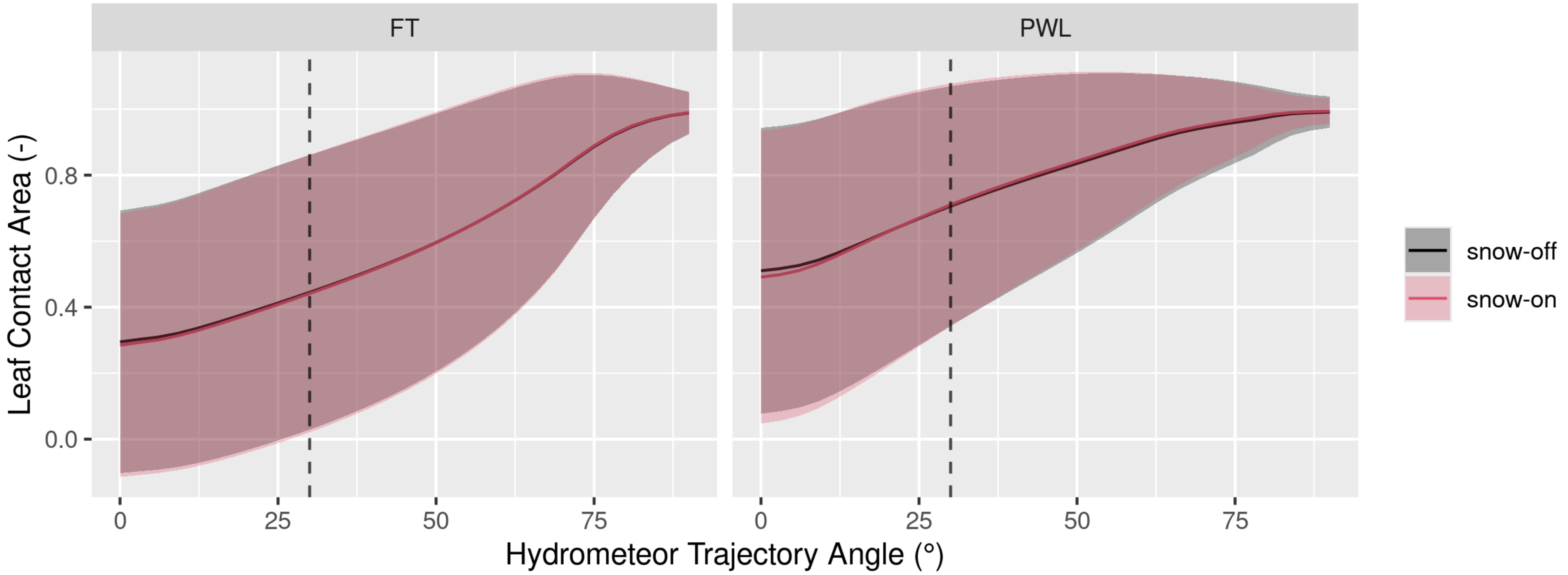


Interception Efficiency for a Wind-driven Snowfall Event

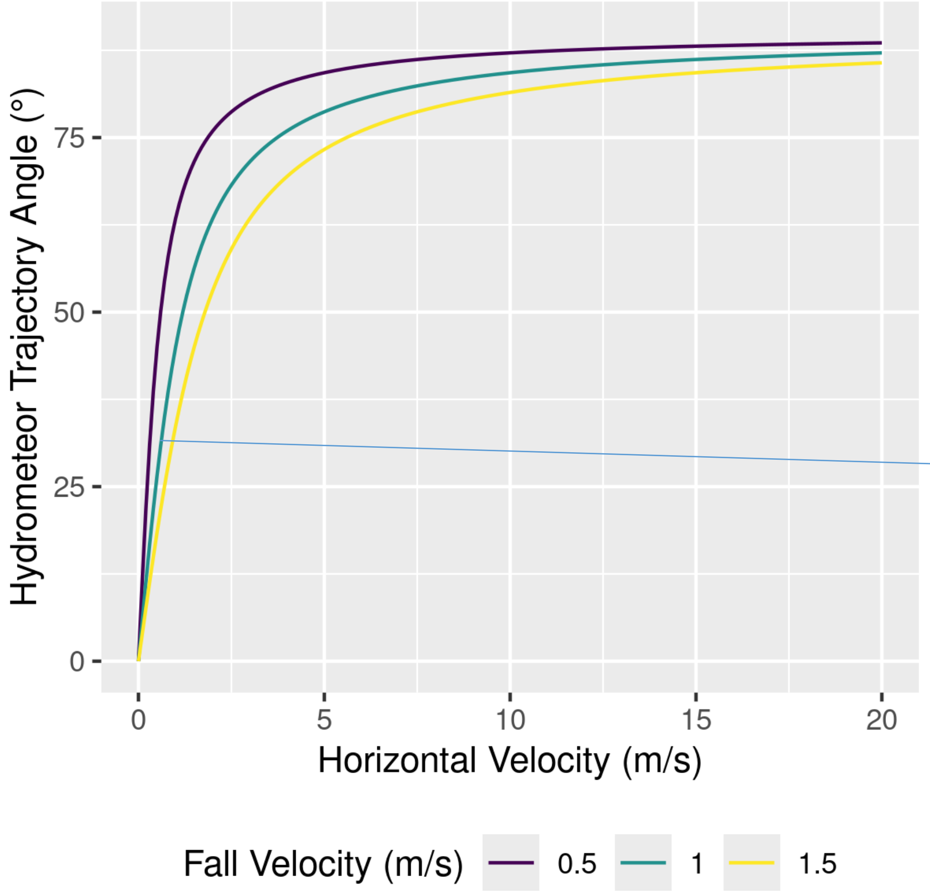
- I/P calculated using lidar **Δ**HS, $\overline{\rho}$, and ΔSWE_o
- ↑ I/P is observed on the lee side (north) of individual trees

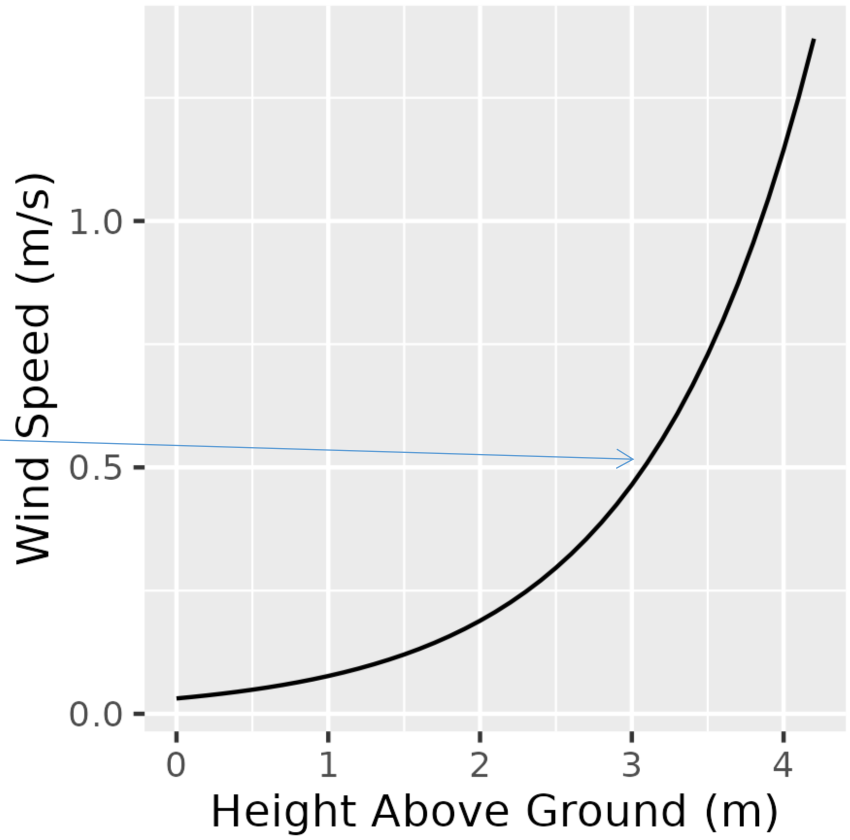


How does canopy snow influence forest structure?



What wind speed height is important for estimating the mean trajectory angle?





- Hemisphere analysis showed trajectory angles up to 30° are important for snow accumulation
- Based on Equation 1, a wind speed of 0.5 m/s would produce a trajectory angle of 30°
- Using Cionco 1965, the observed wind speed at 4.2 m can be scaled down to the ground
- A wind speed of 0.5 m/s is estimated at 3 m above the ground which is ~ 1/2 the FT canopy height and 1/3 the PWL canopy height