Decoupling Snow Interception and Ablation Parameterizations: Insights from High-Frequency and Fine-Scale Observations from a Subalpine Forest

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(**TODO?**) add discussion on linking snow interception process to general hydrological modelling

(**TODO?**) Add ref to Niu & Yang (2004) who considered the influence of solar zenith angle on light transmittance through the canopy. Also ref Dai et al. (2019) who propose a way to represent subgrid variability and gap distribution in the canopy, important for them for subcanopy turbulence.

**Abstract:** Existing subcanopy snow accumulation models differ in their representation of snow interception and ablation processes, with uncertain applicability across diverse climates and forest types. Moreover, some snow interception parameterizations are coupled with ablative processes, leading to poor performance when used in models that are not calibrated to account for this. This study evaluates the theory underpinning these parameterizations and proposes a new snow interception routine using data from two subalpine forest plots in the transitional climate of the Canadian Rockies. In-situ meteorological data, high-frequency point-scale throughfall measurements, and fine-scale aerial lidar measurements of throughfall and canopy metrics were collected. Contrary to existing theories, no association of canopy snow load or air temperature on interception was observed. Instead, forest structure emerged as the primary factor governing snow accumulation at the forest plot scale. A wind-driven snowfall event demonstrated that interception efficiency prediction improved drastically when adjusted for hydrometeor trajectory angle. Leaf contact area showed high sensitivity to wind speed, increasing by up to 95% with a 1 m s-1 wind speed, which significantly reduced throughfall depths across both forest plots. The study proposes two new equations which model snow interception efficiency as a function of leaf contact area adjusted for hydrometeor trajectory angle. This new parameterization successfully estimated interception efficiency for a snowfall event with R2 values of 0.69 and 0.47 for the two forest plots in this study. By minimizing the inclusion of ablative processes, this new model should offer improved uncalibrated performance with existing ablative parameterizations in the literature.

**Keywords:** snow interception, throughfall, ablation, forest, snowpack, lidar, process-based modelling

# 1. Introduction

Over half of North America’s snow covered zone is covered by forests (Kim et al., 2017), significantly impacting the accumulation and redistribution of subcanopy snowpacks and subsequent snowmelt runoff. Researchers have estimated that across the globe, 25–45% of annual snowfall may be lost to the atmosphere due to sublimation of snow intercepted in the canopy (Essery et al., 2003). Snow intercepted in the canopy can sublimate and melt at much higher rates compared to the subcanopy snowpack (Floyd, 2012; Lundberg & Hallidin, 1994; Pomeroy et al., 1998), reducing the amount of snow available for runoff. Forest thinning efforts aimed at limiting sublimation losses and increasing snow accumulation sometimes have expected consequences for snowmelt runoff (Golding & Swanson, 1978; Harpold et al., 2020; Troendle, 1983). This may be due to increased ablation rates when forest cover is reduced and a limited process understanding (Ellis et al., 2013; Musselman et al., 2015; Pomeroy et al., 1997; Safa et al., 2021; Varhola et al., 2010). Vegetation structure controls the partitioning of snowfall into throughfall and interception, and thus governs the quantity of snow subject to sublimation (Hedstrom & Pomeroy, 1998; Storck et al., 2002). The time that snow resides in the canopy, and is available for high rates of sublimation depends on unloading rates (Hedstrom & Pomeroy, 1998; Roesch et al., 2001), canopy snowmelt (Mahat & Tarboton, 2014), and wind redistribution (Wheeler, 1987). Due to the significant impact of forest cover on snow accumulation and ablation, and the absence of a regional scale monitoring network of forest snow accumulation (Rittger et al., 2020; Vionnet et al., 2021), land management, ecological conservation and water resource decisions rely on robust models of snow redistribution to estimate past, current and future subcanopy snowpacks.

Numerous field-based studies have developed methodologies to improve snow interception process understanding to better predict snow accumulation in forests. These methods, discussed in detail in Cebulski & Pomeroy (2024), include snow surveys mass balance (Hedstrom & Pomeroy, 1998), tree weighing (Hedstrom & Pomeroy, 1998; Katsushima et al., 2023; Lundberg, 1993; Satterlund & Haupt, 1967; Schmidt & Gluns, 1991; Storck et al., 2002), gamma ray attenuation (Calder, 1990), subcanopy lysimeters (Storck et al., 2002) and time-lapse imagery analysis (Floyd & Weiler, 2008; Lumbrazo et al., 2022). Cebulski & Pomeroy (2024) noes the care needed in using these methods to isolate interception from ablative processes. As a result, existing parameterizations for snow interception are sometimes coupled to ablative processes (e.g., Hedstrom & Pomeroy, 1998; Katsushima et al., 2023) and may not be compatible when combined with additional ablative process representations in uncalibrated models (Clark et al., 2020; Verseghy, 2017; Wheater et al., 2022). Previous studies have collected measurements of interception efficiency over timesteps ranging from hourly (Storck et al., 2002) to weekly (Hedstrom & Pomeroy, 1998). The varying measurement time intervals affect the duration during which ablative processes may have influenced these measurements and resulting models, leading to potential underestimations of the fraction of snow intercepted in the canopy.

The coupling of ablative processes within existing snow interception models may explain the over estimation of subcanopy snow accumulation reported by Lundquist et al. (2021) and Lumbrazo et al. (2022) when combining the Hedstrom & Pomeroy (1998) routine with ablation parameterizations from different studies (e.g., Roesch et al., 2001). However, Gelfan et al. (2004) demonstrated accurate subcanopy snowpack simulations at study sites across the globe by treating the Hedstrom & Pomeroy (1998) and Storck et al. (2002) parameterizations separately while using a step-based function to choose either parameterization based on temperature. Additional observations of snow interception that minimize the inclusion of ablative processes could help determine if the theories in Hedstrom & Pomeroy (1998) and Storck et al. (2002) are valid for these measurements.

Previous studies have found differing relationships of the canopy snow storage capacity with air temperature (see Figure 6 in Cebulski & Pomeroy, 2024). However, Lundquist et al. (2021) found improved subcanopy snowpack simulations when they omitted the canopy snow storage capacity from Hedstrom & Pomeroy (1998), while utilizing a complete representation of ablation processes. This, combined with studies which have not observed a canopy snow storage capacity (Calder, 1990; Katsushima et al., 2023; Storck et al., 2002), and the potential explanation of decreased interception at higher canopy snow loads in (Hedstrom & Pomeroy, 1998; Moeser et al., 2015; Satterlund & Haupt, 1967) attributed to ablative processes, suggests the canopy snow storage capacity may be much higher than existing models predict. While the storage capacity may not have significant implications for snow loading, it may be beneficial to reformulate ablative parameterizations as a function of canopy snow load for consistency with the rainfall interception literature (e.g., Valante et al., 1997). This could also help process representation particularly in regions that are prone to rime-ice formation, which can limit canopy snow ablation (Lumbrazo et al., 2022) and can lead to heavy snow loads causing stem breakage (Lehtonen et al., 2014, 2016).

The extent that processes observed at the point scale, such as bridging of gaps in canopy elements (Satterlund & Haupt, 1967), or branch bending (Hedstrom & Pomeroy, 1998; Pomeroy & Gray, 1995; Schmidt & Gluns, 1991), influence snow accumulation at the forest plot scale remain uncertain. Fine-scale observations of throughfall have only recently become feasible at the plot scale (Harder et al., 2020; Staines & Pomeroy, 2023), presenting an opportunity to provide more definitive answers to how interception processes vary across differing spatial scales. Existing theory proposed by Hedstrom & Pomeroy (1998) suggests that moderate wind speeds, which result in horizontal hydrometeor trajectories, can increase leaf contact area and thus increase interception efficiency at the plot scale. This association has also been shown in rainfall interception studies (i.e., Herwitz & Slye, 1995; Van Stan et al., 2011) to have a significant influence on observed throughfall of rain. Despite this importance for rainfall, this relationship proposed by Hedstrom & Pomeroy (1998), is typically not included in models (Clark et al., 2020; e.g., Mahat & Tarboton, 2014), as empirical support for this relationship is lacking and it also exhibits a relatively low sensitivity (see Figure 8 in Cebulski & Pomeroy, 2024). New methods developed by Staines & Pomeroy (2023) to characterize the canopy at a high angular and spatial resolution have shown the potential to improve understanding of the relationship between snow interception and forest structure spatially and also across differing trajectory angles. However, these insights have yet to be confirmed for additional study sites with more diverse forest structure and need to be incorporated into a theoretical framework appropriate for modelling snow accumulation in forests.

The objective of this paper is to evaluate the theory underlying existing snow interception models using high-frequency point scale and high spatial resolution measurements of subcanopy snow accumulation that attempt to minimize inclusion of ablative processes. These new observations are investigated to address the following research questions:

1. Are the existing theories regarding the relationship between meteorology and forest structure on snow interception supported by in-situ observations?
2. How is snow interception influenced by non-vertical hydrometeor trajectory angles over a wind-driven snowfall event?
3. To what extent can these findings inform the development of a new parameterization for snow interception?

# 2. Theory

## 2.1 Snow Interception

During calm snowfall periods, where ablative processes could be assumed negligible, the amount of snow intercepted in the canopy was estimated as:

where is the snowfall rate (kg m-2 s-1) and is the throughfall rate (kg m-2 s-1). This method was preferred, compared to direct measurements from the weighed tree lysimeter, as the subcanopy lysimeters were not influenced by sublimation losses from snow intercepted in the canopy. For a complete description of the canopy snow mass and energy balance see Cebulski & Pomeroy (2024).

Over a discrete time interval, , the change in canopy snow load, (kg m-2) was calculated as:

where and are the average snowfall and throughfall rate over (proved by automated instrumentation). is the change in SWE to the open (kg m-2) and (kg m-2) is the change in SWE below the canopy (provided by snow surveys over longer time intervals).

Interception efficiency, (-), which is the fraction of snow intercepted over was calculated as:

## 2.2 Hydrometeor Trajectory Angle

The trajectory angle, of a hydrometeor as the departure in degrees (°) from a vertical plane (i.e., 0° for vertical snowfall), is shown in Herwitz & Slye (1995) to be calculated as:

where is the terminal fall velocity of the hydrometeor (m s-1), which is a function of the hydrometeor diameter, and is the horizontal change in the hydrometeor (m s-1) which is a function within canopy wind speed, at height above ground, .

Above the top of the canopy, wind flow is approximately logarithmic with height. Cionco (1965) show that, may be approximated using the exponential formula:

where is the horizontal wind speed at the top of the canopy which is a function of the friction velocity , height above ground, , roughness length, , and the displacement height of the canopy, . is an attenuation coefficient that increases with increasing leaf area and decreases as the mean distance between individual trees increases, is the height above ground of , and is the average height of the canopy elements. Cionco (1972) suggest values for of 1.01 for small needleleaf trees, Zhu et al. (2001) provide methods to calculated based on canopy density and Parviainen & Pomeroy (2000) provide a method to calculate using observations from two jack pine (*Pinus banksiana*) stands. [Figure 5](#fig-ws-vs-ta) shows the increase in trajectory angle calculated using [Equation 4](#eq-ta) with a constant hydrometeor velocity of 1 m s-1 and a horizontal velocity equal to mid-canopy wind speeds ranging from 0-20 m s-1.

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| Figure 1: Plot showing the relationship of hydrometeor trajectory angle (departure from zenith) with increasing horizontal velocity from [Equation 4](#eq-ta). The three different lines represent fall velocities of 0.5 m s-1 (purple), 1 m s-1 (green), 1.5 m s-1 (yellow). |

# 3. Data and Methods

## 3.1 Study Site

This study was conducted at Fortress Mountain Research Basin (FMRB), AB, -115° W, 51° N, a continental headwater basin situated within the Canadian Rocky Mountains ([Figure 2](#fig-site-map)). Data from this study was collected between October 2021 and July 2023 within and surrounding two forest plots adjacent to the FMRB Powerline Station (PWL) and Forest Tower Station (FT) at ~2100 m asl. ([Figure 2](#fig-site-map)). The average annual precipitation at PWL Station from 2013 to 2023 is 1045 mm, with the peak annual snow water equivalent (SWE) reaching 465 mm, typically occurring in late April. The PWL and FT forest plots include discontinuous stands of subalpine fir (Abies lasiocarpa) and Engelmann spruce (Picea engelmannii) trees, with a proportion of 70% and 30% respectively (Langs et al., 2020). In the early 1900s the majority of vegetation in the FMRB burned during a large forest fire that affected most of the Kananaskis Valley. Following the fire, the forest within the the PWL and FT forest plots has naturally regenerated with minimal disturbance. The average height of the canopy surrounding the plot to the east of the PWL station is 10.51 m and surrounding the forest plot around the FT Station is 7.12 m. The canopy coverage of the PWL and FT forest plots is 0.51 and 0.29 respectively.

## 3.2 Meteorological Measurements

A flux tower at the FT Station provided measurements of air temperature (Campbell Scientific HMP155A), relative humidity (Campbell Scientific HMP155A), wind speed (Campbell Scientific Ultrasonic-86000 & Metone 014A) and wind direction (Campbell Scientific Ultrasonic-86000) at 15-min time intervals 4.3 m above the ground ([Figure 2](#fig-site-map)). The PWL station, located 120 m to the northwest of FT station in a forest clearing shown in [Figure 2](#fig-site-map) provided measurements of snowfall rate, additional wind speed measurements and hydrometeor size and velocity. The snowfall rate was measured using a weighing precipitation gauge 2.6 m above ground (OTT Pluvio) corrected for undercatch following phase correction by Harder & Pomeroy (2013) and catch efficiency by Macdonald & Pomeroy (2007). A Metone 014A anemometer provided wind speed measurements at a height of 2.6 m, while the RM Young anemometer recorded wind speed and wind direction at a height of 5.2 m. A disdrometor (OTT Parsivel2) provided measurements of hydrometeor particle size and velocity.

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| Figure 2: Map showing the location of forest plots, flux towers, SCL instruments and survey transects. Inset map on the lower right shows the regional location of Fortress Mountain Research basin. |

The met conditions observed over the snowfall periods are illustrated in: (had a paragraph on this before look for old manuscript version)

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| Figure 3: Histogram of meterological conditions for periods with snowfall and minimal unloading. |

Need to put interception measurements for automated analysis with meteorology into context of wind direction that is primarily from the southwest which the medium trough has a canopy opening in that direction.

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| Figure 4: Wind rose over all periods of snowfall with minimal unloading. |

## 3.3 Lysimeter Data

Three subcanopy lysimeters (SCLs) were installed surrounding the FT Station to provide fifteen minute interval measurements of throughfall and unloading (see locations in [Figure 2](#fig-site-map)). The SCLs consisted of a plastic trough with an opening of 0.9 m 2 and depth of 20 cm suspended from a load cell (Intertechnology 9363-D3-75-20T1) attached to an aluminum pipe connected between two trees. The load cell which measures kilograms was scaled to kg m-2 by dividing by the cross-sectional area of the SCL opening. For select time periods where ablative processes including, unloading, drip and wind redistribution could be considered negligible, the subcanopy lysimeters were inferred to provide measurements of throughfall (see method described in Cebulski & Pomeroy, 2024). Interception efficiency was calculated using [Equation 2](#eq-dwdt-discrete) and [Equation 3](#eq-ip), combined with from the three SCLs and from the PWL snowfall gauge. For each of the 26 snowfall events the average interception efficiency over each event was calculated for each 15-minute timestep within the 26 snowfall events. Timelapse imagery, a weighed tree and in-situ observations were used to ensure the ablation of snow intercepted in the canopy or snow on the ground was minimal over each of the selected events. The canopy structure surrounding three SCLs and was measured using hemispherical photography (Nikon Coolpix 4500 and EC-F8 hemispherical lens) and the hemispheR R package Chianucci & Macek (2023) and is shown in [Table 1](#tbl-scl-lai-cc).

Positioning of the troughs leads to differing influence of wind on I/P.

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| Figure 5: Positioning of the troughs leads to differing influence of wind on I/P. |

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| Table 1: Canopy structure of the three subcanopy lysimeters (SCL) located proximal to the FT Station. Leaf area index (LAI) and Canopy Coverage was measured using hemispherical photo analysis with the R package hemispheR.   | Name | LAI (-) | Canopy Coverage (-) | | --- | --- | --- | | SCL Low | 1.59 | 0.73 | | SCL Med | 1.86 | 0.78 | | SCL High | 2.11 | 0.82 | |

A weighed tree lysimeter, measured the weight of canopy snow load, (kg). A live subalpine fir (Abies lasiocarpa) tree was cut and suspended from a load cell (Artech S-Type 20210-100) at the beginning of the 2022 and 2023 water years which recorded the weight of the tree. The bottom of the tree was sealed to limit some transpiration and to prevent spinning and abrupt impacts of the free-hanging tree, the base of the tree was attached to a support system that allows for vertical movement but limits abrupt horizontal movements. The weight of snow in the weighed tree in kg was scaled to an areal estimate of canopy snow load (, kg m-2) using measurements of areal throughfall (kg m-2) from manual snow surveys and snowfall from the PWL Station snowfall gauge (see description of method in Hedstrom & Pomeroy, 1998). While not used in the computation of interception efficiency, the weighed tree provided a continuous measurement of which were used to filter out periods of canopy snow ablation identified by periods of time that exhibited a loss in .

## 3.4 UAV Data Processing

Two uncrewed aerial vehicle (UAV) lidar surveys were conducted before and after a 24 hour snowfall event that occurred between March 13th and March 14th, 2023. These surveys were undertaken to facilitate the measurement of snow accumulation and canopy structure metrics. The UAV (FreeFly Alta X) was equipped with a REIGL miniVUX-2 airborne laser scanner payload, an Applanix APX-20 inertial measurement unit (IMU) and global navigation satellite system (GNSS). The UAV was flown 90 m above the ground at a speed of 3 m s-1 following a preprogrammed flight trajectory shown in [Figure 2](#fig-site-map).

The REIGL miniVUX-2 laser operates at a near infrared wavelength with a laser beam footprint of 0.160 m x 0.05 mm (at 100 m above ground). The accuracy and precision of the miniVUX-2 is described by REIGL for a lab environment of 0.015 m and 0.01 m respectively (at 50 m above ground). The miniVUX-2 was configured with a laser pulse repetition rate of 200 kHz, field of view of 360°, scan speed of 31.09 revolutions s-1 and an angular step width of 0.0558°, resulting in an expected an average point cloud density of 107 returns m-2 for each flight path.

Georeferenced point clouds with x, y, and z coordinates for each laser return were generated following methods outlined by Harder et al. (2020) and Staines & Pomeroy (2023) to reconcile survey lidar, IMU and GNSS data. A ground based GNSS system was positioned on a permanent monument during each survey and underwent precise point positioning (PPP) correction by Natural Resources Canada (2024). Differential GNSS correction of the UAV trajectory was conducted using the ground based PPP GNSS observations and the POSPac UAV software. The UAV-lidar point clouds were then transformed from a sensor referenced coordinate system to a georeferenced coordinate system (EPSG:32611 - WGS 84 / UTM zone 11N) using the RIEGL Riprocess Software. A vertical offset of up to 6 cm between UAV-lidar flight lines was observed in the resulting point clouds on March 13th and 14th, 2024 and was attributed to IMU position drift. This offset between flight lines was corrected using the BayesStripAlign software v2.24 (BayesMap Solutions, 2024), which reduces relative and absolute uncertainties in the vertical elevation of the point cloud using the ground control points (GCP) collected across the study site using a differential GNSS rover. After strip alignment, the mean elevation bias (lidar minus GCP) was 0.000 m and the RMS error changed from 0.055 m to 0.038 m March 13th and changed from 0.033 m to 0.029 m on March 14th. The point cloud density ranged from ~1200 returns m2 in open clearings to ~2200 m2 in sparse forest for both the March 13 and 14th surveys after all flight paths were combined.

Quality control, ground classification and calculation of the change in between two UAV-lidar point clouds was conducted using the LAStools software package (LAStools, 2024). The ground classification was conducted using the “lasground\_new” function (LAStools, 2024) for both the pre and post snowfall event point clouds, with a step size set to 2 m and 8 substeps (ultra\_fine setting). The offset and spike options were set to remove points that are more than 0.1 m above or below the initial ground surface estimate surface which “lasground\_new” fits to the last returns. This function is based on an algorithm outlined by Axelsson (2000), describing the process of making the initial ground surface element.

## 3.5 Snow Surveys

### 3.5.1 In-situ Snow Depth and Density

In-situ fresh snow surveys provided measurements of subcanopy throughfall following the transects shown in [Figure 2](#fig-site-map). Twelve fresh snow surveys (six pre and post snowfall event pairs) at 30 stations were selected which had minimal ablation and redistribution between pre and post surveys and were used to scale the weighed tree following methods outline in Hedstrom & Pomeroy (1998). When conditions allowed for a UAV-lidar flight, the in-situ snow surveys were conducted following the UAV-lidar flight to assess the accuracy of the throughfall measurements and provide a fresh snow density for the calculation of SWE (kg m-2). A 1000 cm3 snow density wedge sampler (RIP Cutter, https://snowmetrics.com/shop/rip-1-cutter-1000-cc/) was used to measure the density of the fresh snow layer, (kg m-3). The throughfall depth measurements, were converted to SWE using the following equation:

Differential GNSS rover coordinates, with ± 2.5 cm 3D uncertainty, were taken at each snow sampling location so the locations could be queried later from the UAV-lidar rasters. If a pre event crust layer was present the depth of post event fresh snow accumulation above the crust layer were interpreted as throughfall over the event. In the absence of a defined crust layer, the difference in pre and post event snow depth to ground was interpreted as event throughfall.

### 3.5.2 UAV-Lidar Snow Depth

Two UAV-lidar surveys were selected for detailed analysis in this study, one prior to a snowfall event on March 13, 2023 at 10:00 CST and another following snowfall on March 14, 2023 at 11:00 CST. These two surveys enabled fine-scale analysis of snow accumulation and canopy structure within the FT and PWL forest plots. This snowfall event was selected based on two criteria: 1) it provided sufficient cumulative snowfall to result in a low relative error in UAV-LiDAR measured throughfall, and (2) minimal redistribution and ablation were observed over the event, as confirmed by the SCLs, weighed tree, and time-lapse imagery. The change in elevation between the two UAV-lidar surveys was interpreted as the increase in snow accumulation, over the snowfall event. This change was calculated using a point-to-grid subtraction method, using the “lasheight” function from the LAStools (2024) software, as in Deems et al. (2013) and Staines & Pomeroy (2023). The pre snowfall event point cloud from “lasground\_new” by “lasheight” to construct a “ground” TIN. Subsequently, the height of each post snowfall event point above the ground TIN, resulting in a point cloud representing . This point cloud was then converted into a raster of with a grid cell resolution of 5 x 5 cm using the “las2dem” function. Further quality control and resampling of the 5 cm raster of was conducted using the ‘Terra’ R package (Hijmans, 2024). Regions that were disturbed over the snowfall event during the in-situ snow survey and values that exceeded the .999th quantile were removed. To help remove any remaining noise a 25 cm raster was generated by computing the median of the 5 cm values within each 25 cm grid cell.

## 3.6 UAV-Lidar Canopy Metrics

The point cloud and trajectory data acquired from the two UAV-lidar surveys were also utilized to characterize the canopy structure of the FT and PWL forest plots. To characterize the canopy structure, the voxel ray sampling (VoxRS) methodology for lidar data analysis was employed, as outlined by Staines & Pomeroy (2023). This method was chosen for its ability to provide canopy metrics that are less sensitive to the inherent non-uniform nature of lidar sampling data, which often results from beam occlusion in vegetation and leads to reduced points near the ground. The VoxRS algorithm is publicly available at https://github.com/jstaines/VoxRS. The canopy products produced from VoxRS here include: canopy contact number, the mean theoretical number of canopy contacts for a given ray, and radiation transmittance () all with units (-). See supporting information in Staines & Pomeroy (2023) for details on how these metrics are computed. The fraction of snow-leaf contact area per unit area of ground used in Hedstrom & Pomeroy (1998), and hereafter called leaf contact area (), was calculated as:

where is a function of the canopy coverage , and . is approximately equal to canopy coverage () for vertical snowfall. However, for non-vertical snowfall .

## 3.7 Correlation Between Forest Structure and Interception

To determine how forest structure was associated with interception efficiency at different azimuth and zenith angles over the March 13-14 snowfall event, each portion of the hemisphere at each grid location was considered. The relationship between interception efficiency and canopy contact number was found to be linear and thus the Pearson Correlation Coefficient, was calculated using the ‘stats’ package in R (R Core Team, 2022) to quantify the association between a single raster of interception efficiency and the 32’760 rasters containing the canopy contact number hemisphere for each portion of the hemisphere (azimuth [0°, 1°, …, 359°], zenith angle [0°, 1°, …, 90°]) for each of the 25 cm grid cells across the FT and PWL forest plots.

## 3.8 Regression Models

Linear and non-linear models, based on observed data and theoretical justification presented in this study, were developed and assessed using the ‘stats’ package in R (R Core Team, 2022). Linear models were fitted using ordinary least squares regression via the ‘lm’ function to analyze two relationships: (1) between interception efficiency and leaf contact area, and (2) between leaf contact area and trajectory angle. Both models were forced through the origin based on the theoretical justification that the dependent variable should be zero when the independent variable is zero. To assess the performance of the linear models, we calculated four metrics comparing observed and modelled values: mean bias, mean absolute error (MAE), root mean square error (RMSE), and the coefficient of determination (R2). Following Kozak & Kozak (1995), we recognized that the default R2 value provided for least squares models forced through the origin by many statistical packages can be misleading. Therefore, we adjusted these R2 values using Equation 10 in Kozak & Kozak (1995). Although we had theoretical justifications for forcing the intercept through the origin, we also employed two statistical tests as described by Kozak & Kozak (1995) to verify whether a no-intercept model (forced through the origin) was appropriate for our data compared to a with-intercept model (including an intercept). The first test evaluated if the intercept of the with-intercept was significantly different from zero using p-value provided by the ‘summary’ function from the ‘stats’ package in R. The second test examined if there was a significant difference between the no-intercept and with-intercept models by testing if the residual sum of squares was different between the no-intercept and full model, assessed via Equation 15 in Kozak & Kozak (1995). If the first test indicated a significant difference, and the second did not, the no-intercept model could be deemed statistically justified (Kozak & Kozak, 1995). Non-linear models were fitted using non-linear least squares regression via the ‘nls’ function in ‘stats’ package in R. The non-linear models were assessed by comparing predicted values to observed values using three metrics: mean bias, mean absolute error (MAE), root mean square error (RMSE), and R2.

# 4. Results

## 4.1 The influence of meteorology on snow interception

[Figure 6](#fig-scl-w-sf) depicts the state of canopy snow load with increasing cumulative snowfall, measured for 26 snowfall events using the three SCLs and the PWL snowfall gauge. Canopy snow load was observed in [Figure 6](#fig-scl-w-sf) to increase linearly with increasing snowfall without evidence of reaching a maximum canopy storage capacity. Variation in the slope of each line in [Figure 6](#fig-scl-w-sf), is attributed to differences in the meteorology and antecedent canopy snow load within and between the individual events. Variations in the canopy structure surrounding the SCL instruments as shown in [Table 1](#tbl-scl-lai-cc), also contributed to the difference in slope. The absence of canopy snow load measurements in [Figure 6](#fig-scl-w-sf) for certain troughs during specific events was caused by damage to the subcanopy lysimeter wiring due to animal interference and snow load.

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| Figure 6: Plot showing the cumulative event snowfall versus the corresponding state of canopy snow load calculated using the SCLs for each of the 26 snowfall events. The SCLs are denoted by a distinct colour (grey, yellow, and green), correspond to varying canopy coverage (0.73, 0.78, and 0.82, respectively). |

(**TODO?**) could change met ip fig to show less bins (maybe just 2 as in the wilcoxon test or could do three and change to a non parametric anova - Kruskal-Wallis test)

[Figure 7](#fig-lai-met-ip) shows the association between interception efficiency measured by the three SCLs and the corresponding air temperature, wind speed, canopy snow load for the same 15-minute time interval. The mean interception efficiency measured by the SCLs is 0.54, 0.57, and mean\_ip\_dense for the sparse, medium, and dense density forest instruments respectively. Panel A in [Figure 7](#fig-lai-met-ip) shows the average air temperature measured at FT station has very low correlation between non-binned observations (R2 < 0.04, **p** < 0.05) ). The average interception efficiency observed within air temperature bins also does not visually exhibit any systematic trend. A non-parameteric Wilcoxon signed rank test comparing the median interception efficiency below and above -6 °C, showed a significantly greater median interception efficiency (**p** < 0.05) for the cold group compared to the warm groups for all three lysimeters.

Panel B in [Figure 7](#fig-lai-met-ip) in Wind speed measured at FT Station showed a positive association with interception efficiency at the dense\_forest and sparse\_forest lysimeters. The non-binned 15-minute observations of wind speed and air temperature showed very low correlation with the R2 ranging between 0.04 and 0.08 (**p** < 0.05) for all three troughs. The correlation observed between the sparse\_forest and dense\_forest SCLs was observed to be positive, while the medium\_density\_forest SCL exhibited a negative correlation. Between wind speed bins of 0.25 and 2.75 m s-1 the mean interception efficiency increased from 0.58 to 0.66 and 0.48 to 0.61 for the dense\_forest and sparse forest SCLs respectively ([Figure 7](#fig-lai-met-ip), B). The medium\_density\_forest SCL declined from 0.59 to 0.45 for the same range in wind speed bins. A comparison of low (< 1 m s-1) and high (> 1 m s-1) wind speeds by the Wilcoxon signed rank test showed that high wind speeds had significantly higher (**p** < 0.05) interception efficiency compared to the low wind speed group for each SCL. Conversely, the Wilcoxon test showed the medium\_density\_forest SCL had significantly higher (**p** < 0.05) interception efficiency for the low wind speed group. scomparing the median interception efficiency below and above -6 °C, showed a significantly greater median interception efficiency (**p** < 0.05) for the cold group compared to the warm groups for all three lysimeters. For the dense\_forest and sparse\_forest this increase in interception efficiency is interpreted to be due to an associated increase in canopy contact area as hydrometeor trajectory becomes more horizontal with increasing wind speed. The canopy surrounding the medium\_density\_forest SCL is open (see [Figure 2](#fig-site-map)) to the prevailing wind direction, shown in [Figure 4](#fig-wind-rose), observed over the snowfall events included in this analysis and therefore showed a opposing relationship as the trajectory of hydrometeors primarily entered the SCL through this opening to the southwest rather than directly overhead which may have have more canopy elements intercepting snowfall.

[Figure 7](#fig-lai-met-ip), panel C shows the canopy snow load, measured at the beginning of each timestep and shows a relatively weak significant negative relationship between the 15-minute observations (R2 < 0.4, **p** < 0.05) for the dense\_forest and sparse\_forest SCLs and a non-significant relationship was observed for the medium\_density\_forest SCL. The binned data show a small increase in interception efficiency was observed for all three troughs between canopy snow loads of 0 mm to 7 mm. This was followed by a gradual decline in interception efficiency for snow loads greater than 7 mm with the dense\_forest and sparse\_forest SCL ([Figure 7](#fig-lai-met-ip), C). The interception efficiency measured by the medium\_density\_trough SCL also declines above 7 mm before increasing again around 16 mm and then declines again to a minimum interception efficiency of 0.39. A comparison of low (< 10 mm) and high (> 10 mm) canopy snow loads using the Wilcoxon rank-test showed the low canopy snow loads had significantly greater (**p** < 0.05) median interception efficiency compared to the high canopy snow load group. The location of the SCLs within gaps in the canopy may have contributed to these instruments registering a slight increase in interception efficiency as small branch gaps are covered by snow followed by a decline in interception efficiency as branches bend due to the weight of snow intercepted on the branch compressing it downwards and thus reducing the canopy coverage above the SCLs. No association was observed between hydrometeor diameter and hydrometeor velocity and interception efficiency.

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| Figure 7: Scatter plots of discrete observations (blue dots) and binned data (black dots with error bars) of meteorology, canopy load, and hydrometeor characteristics versus snow interception efficiency. Panels show (A) air temperature, (B) relative humidity, (C) wind speed, (D) initial canopy snow load (the snow load observed at the beginning of the timestep), (E) hydrometeor diameter, (F) hydrometeor velocity. The black open circles show the mean of each bin and the error bars represent the standard deviations. The data were filtered to include observations with a snowfall rate > 0 mm/hr, throughfall rate > 0.05 mm/hr to minimize noise and a snowfall rate > the subcanopy lysimeter throughfall rate to minimize observations with unloading. Periods of unloading and melt were also removed through careful analysis of the weighed tree, subcanopy lysimeters, and timelapse imagery. |

## 4.2 The influence of forest structure on snow interception

UAV-lidar measurements of throughfall and canopy structure metrics provided insights on how the forest canopy influenced subcanopy snow accumulation during the March 13-14 snowfall event. This event totalled 28.4 mm at the PWL snowfall gauge and was characterized by a transition from low rates of snowfall and air temperature near 0°C to higher rates of snowfall late afternoon on March 13 coinciding with air temperatures around -2.5 °C. An average wind speed of 1.63 m s-1 and direction of 188° was observed over the wind speed profile within the canopy ([Figure 9](#fig-wind-profiles)). UAV-lidar measurements of throughfall shown in [Figure 8](#fig-lidar-tf-ip), used in the calculation of interception efficiency, aligned well with 28 in-situ manual throughfall measurements with a mean bias of -0.001 m and RMSE of 0.024 m. All three SCLs and the weighed tree registered a 2 mm unloading event during a brief pause in snowfall early in the morning on March 14, prior to the UAV-lidar flight. This unloading event in addition to the moderate wind speeds observed during the snowfall event likely contributed to some redistribution of snow on the ground. The relatively small unloading event compared to the amount of snow that fell during the snowfall event and minimal evidence of observed wind redistribution on the ground is inferred to have not significantly altered the UAV-lidar throughfall measurements but may slightly alter the interpretations of these results. [Figure 8](#fig-lidar-tf-ip) shows the spatial distribution of interception efficiency across the study site, calculated using [Equation 3](#eq-ip) and from UAV-lidar measurements, along with from the PWL snowfall gauge. Greater interception efficiency is observed on the north (lee) side of individual trees, which is interpreted to be a result of non-vertical hydrometeor trajectories caused by the steady southerly winds observed over this event. This effect is shown in [Figure 8](#fig-lidar-tf-ip) to be more apparent within the PWL forest plot, compared to the FT forest plot. This may be attributed to the taller trees and higher canopy coverage within the PWL forest plot compared to the FT forest plot, where given the same trajectory angle a taller tree will produce a larger footprint.

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| Figure 8: UAV-lidar measurements of the change in SWE (kg m-2) and interception efficiency over the March 13, 2023 24 hr snowfall event for the FT and PWL forest plots at a 25 cm resolution. Transparent areas represent grids that did not have any lidar ground returns (i.e., under dense canopy proximal to tree trunks) or have been masked due to disturbance. See the location of the two forest plots within FMRB in [Figure 2](#fig-site-map). |

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| Figure 9: Wind speed profile fit to average wind speeds over the March 13-14 snowfall event from anemometors at 3, 4, and 15 m above ground at FT station. The wind profile was computed for heights above the snowpack which was 1.47 m on average over the event. |

[Figure 10](#fig-hemi-ip-cc) presents two hemisphere plots which illustrate the correlation between and interception efficiency over differing azimuth and zenith angles for both the FT and PWL forest plots. These plots demonstrate a strong correlation between and interception efficiency towards the southern portion of the hemisphere, aligning with the average wind direction observed during the event. For the PWL forest plot, the upper 97.5th percentile of the values shown in [Figure 10](#fig-hemi-ip-cc), were found between azimuth angles of 167° – 217°. Similarly, for the FT forest plot, the upper 97.5th percentile of was found between azimuth angles of 171° – 223°. To determine what zenith angle had the strongest correlation with interception efficiency, a second correlation was run between interception efficiency and calculated over the aforementioned range in azimuth angles for each respective plot. The zenith angle found to have the highest correlation over this azimuth range was 22° ( = 0.7) and 21° ( = 0.83) for PWL and FT respectively. The high correlation coefficients found for non-vertical zenith angles for both PWL and FT are interpreted to be a result of inclined hydrometeor trajectories. At near-nadir zenith angles, [Figure 10](#fig-hemi-ip-cc) illustrates slightly lower . In addition to the inclined hydrometeor trajectories, this may be influenced by reduced UAV-lidar returns and higher error proximal to the trunks of individual trees, as shown in [Figure 8](#fig-lidar-tf-ip). However, this limitation does not significantly alter the interpretation of the results.

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| Figure 10: The Pearson Correlation Coefficient between rasters (25 cm resolution) of interception efficiency and leaf contact area for each grid cell across the study site for each azimuth angles (0°, 1°, …, 359°) and zenith angles (0°, 1°, …, 90°) for the FT (left) and PWL (right) forest plots. |

[Figure 11](#fig-lca-vs-ip) shows that the correlation between UAV-lidar measured and interception efficiency, resampled to a 5 m resolution, is stronger when is adjusted for the observed shift in hydrometeor trajectory (Vector Based), compared to the nadir leaf contact angle (zenith angle of 0°). For the vector based model, leaf contact area was measured following the azimuth range and zenith angle with the highest for each plot mentioned in the previous paragraph. An ordinary least squares linear regression forced through the origin was fit to the observed data points using the following equation:

where is an efficiency constant which determines the fraction of snowflakes that contact the elements and are stored in the canopy (i.e., intercepted) before canopy snow unloading or ablation processes begin.

For the FT plot the Nadir linear regression model provides a good overall fit to the observed data (R2 of 0.51) and closely follows the 1:1 line in [Figure 11](#fig-lca-vs-ip), with some significant scatter. For the PWL plot, the observed points follow a linear relationship until a value of around 0.50 after which the increase in interception efficiency plateaus. As a result, after the Kozak & Kozak (1995) adjustment a negative R2 value for the PWL plot resulted. Some of the scatter observed in [Figure 11](#fig-lca-vs-ip) for the Nadir panel may be explained by grid cells which observed a greater interception efficiency compared to the corresponding value, and can be attributed to the inability of to represent the increase in interception observed within canopy gaps in [Figure 8](#fig-lidar-tf-ip). Conversely, for grid cells where interception efficiency is less than , may be attributed to non-vertical trajectory hydrometeors making their way underneath the canopy as observed by the reduced interception efficiency on the windward edges of individual trees in [Figure 8](#fig-lidar-tf-ip). This later explanation explains the non-linear relationship observed for the PWL Nadir model in [Figure 8](#fig-lidar-tf-ip).

For the Vector Based model, the relationship between interception efficiency and is better represented by a linear regression model for both plots with R2 values of 0.47 and 0.8 for PWL and FT respectively. The increase in interception efficiency with follows a reduced slope compared to the Nadir models with values of 0.71 and 0.68 for the PWL and FT plots respectively. The reduced slope for the Vector Based models may be attributed to snowflakes that weaved through and/or bounced off branch elements in addition to some of the UAV-lidar measurement uncertainty which contained some unloading and redistribution. These processes would have acted in concert to reduce the fraction of snowfall that contacted the canopy that was intercepted.

Model error statistics are presented in [Table 2](#tbl-ip-mod-err) for the Nadir and Vector Based models. The Vector Based model improved predicted interception efficiency reducing the RMSE from 0.099 to 0.062 for the FT plot and 0.146 to 0.095 for the PWL plot. The good model performance shown for the Vector Based model demonstrates that using adjusted for observed event hydrometeor trajectory angle has the potential to be a predictor of interception efficiency, before ablation. However, the detailed point clouds required to derrived the values used in this analysis are rarely available and thus more accessible methods to obtain a proxy of must be obtained if [Equation 9](#eq-lca-ip) is to be employed in earth system models.

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| Figure 11: Scatter plots showing the relationship between leaf contact area and interception efficiency rasters resampled to a 5 m grid cell resolution. The left plot (Nadir) shows leaf contact area measured from a zenith angle of 0°. The right plot (Vector Based\*) shows the leaf contact area averaged over rasters with zenith angles (PWL = 22°, FT = 21°) and azimuth angles (PWL = 167°, 178°, … 217°; FT = 171°, 172°, … 223°). The solid lines (Model fit) show the ordinary least squares linear regression forced through the origin and fit to the UAV-lidar measured data for the PWL (red) and FT (black) forest plots. The light grey dotted line shows a 1:1 line. The R^2 values for the four different models are shown in the upper right of each panel calculated following the methods outlined in Kozak & Kozak (1995). |

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| Table 2: Model error statistics provided for predictions of interception efficiency using [Equation 9](#eq-lca-ip) and for different values, as shown in the Model Slope column. Statistics are provided for the PWL and FT forest plots, using leaf contact area canopy metrics adjusted to zenith angles of (0°, 1°, … 30°) and azimuth angles (170°, 171°, … 220°) and nadir zenith angle of 0°. The Mean bias is the difference in the model and observed values, MAE is the mean of the absolute error, RMS Error is the root mean squared error, R^2 is the coefficient of determination adjusted using Equation 10 in Kozak & Kozak (1995).   | Plot Name | Canopy Metrics | Model Slope | Mean Bias | MAE | RMS Error | R^2 | | --- | --- | --- | --- | --- | --- | --- | | FT | Nadir | 0.993 | 0.022 | 0.071 | 0.099 | 0.507 | | FT | Vector Based | 0.676 | 0.001 | 0.047 | 0.062 | 0.804 | | PWL | Nadir | 0.949 | 0.048 | 0.113 | 0.146 | NA | | PWL | Vector Based | 0.707 | 0.019 | 0.078 | 0.095 | 0.469 | |

## 4.3 Determining the hydrometeor trajectory angle

To utilize [Equation 9](#eq-lca-ip), estimates of are needed which are proposed here to be a function of and . Measurements of are commonly available across the globe, however, methods to estimate are dependant on wind speed and hydrometeor velocity and are more uncertain. Estimates of snowflake terminal fall velocity are less sensitive (see **?@fig-ws-ta**) while the wind speed is highly dependent on the height above the ground Cionco (1965).

To determine the height or range in heights above the ground that wind speed is best suited for predicting , and that best aligns with in [Figure 10](#fig-hemi-ip-cc), a wind speed profile was fit using a logarithmic function to observed average wind speeds from three anemometers installed at 3, 4, and 15 m above ground at FT station. The parameters for the wind speed profile fit to the wind speed observations include a roughness length of 0.50 m, displacement height of 0.58m and a friction velocity observed over the March 13-14 event of 0.37 m s-1. Using a logarithmic wind speed profile with these parameters provided a good fit to the observed wind speeds over the event and [Figure 9](#fig-wind-profiles) shows that the within canopy flow equation provided by Cionco (1965) was not appropriate for this study site.

[Figure 9](#fig-wind-profiles) shows predicted hydrometeor trajectory angles at varying heights, calculated using [Equation 4](#eq-ta) and the mean observed hydrometeor terminal velocity observed over the event of, 0.9 m s-1, are higher for the top of the canopy as a result of the higher wind speed, for example at 10 m a trajectory angle of 71.78° was calculated, compared to a trajectory angle of 47.24° at 2 m above the snowpack. The average wind speed observed over the wind profile, calculated as an integral over the range in heights from the displacement height plus roughness height to the average height of the FT plot trees was 1.63 m s-1. The corresponding trajectory angle resulting from this average wind speed was ft\_mean\_wind\_prof\_integral$traj\_angle |> round(2)° calculated using [Equation 4](#eq-ta), and is much higher than the trajectory angle closer to 20° observed in [Figure 10](#fig-hemi-ip-cc). Based on this wind speed profile the trajectory angles of around 20° observed for PWL and FT in [Figure 10](#fig-hemi-ip-cc) would have resulted from a mean wind speed of around 0.35 m s-1 and a height above the snowpack of about 1.3 m. The low height required to achieve this low wind speed is interpreted to be a result of the conical shape of the needleleaf trees surrounding PWL and FT which have the majority of their needleleaf elements lower towards the ground. Although the wind speeds were observed to be higher near the top of the canopy, corresponding to higher trajectory angles, the reduced amount of needleleaf elements at this height result in a smaller impact of these more horizontal trajectories.

## 4.4 The combined influence of trajectory angle and forest structure on interception

Results from VoxRS show that , when aggregated at the forest plot scale, over all azimuth angles shows a positive relationship with simulated hydrometeor trajectory angle and as a result, wind speed as well. The mean leaf contact area (see top row, [Figure 12](#fig-lca-ht-ws)), , observed from VoxRS across each forest plot increases steadily with increasing simulated hydrometeor trajectory angle prior to snowfall on March 13th. The relationship of the increase in leaf contact area from nadir measured leaf contact area with increasing trajectory angle (see bottom row, [Figure 12](#fig-lca-ht-ws)), calculated as is similar for both forest plots FT and PWL until trajectory angles reach approximately 60°. Beyond 60°, the PWL rate of increase slows as the approaches .90 around 60°, while the FT plot, which has lower , continues to rise quickly until around 75° afterwards the slope is reduced as a of one is approached.

The large range in over all trajectory angles, illustrated by the shaded area in [Figure 12](#fig-lca-ht-ws) exhibits the significant scatter across individual grid cells of each forest plot. This large scatter suggests the observed relationships in [Figure 12](#fig-lca-ht-ws) are only applicable at the forest stand scale where smaller deviations due to sub metre variability in the change in with trajectory angle such as a large increase in lee sides of individual trees and little change in the upwind side of some areas of the forest plot, i.e., direction specific differences average out… begin to average out and show a overarching trend.

At the stand scale, increasing the hydrometeor trajectory angle results in a substantial rise in the VoxRS observed over relatively common wind speeds. For example, with a wind speed of 1 m s-1 which leads to a trajectory angle of 48° using [Equation 4](#eq-ta), the increased by a fraction of 0.14 and 0.12 for the PWL and FT forest plots respectively in [Figure 12](#fig-lca-ht-ws) (right panel). This is a percent increase in the plot from nadir of 28% and 40% for PWL and FT respectively. was also quantified across trajectory angles for both PWL and FT on March 14th, post snowfall, and showed a negligible effect of canopy snow load on . A similar rate of increase in was observed between both the FT and PWL forest plots up to around 60° and suggests a similar function may be able to be used for corresponding wind speeds under 1.5 m s-1.

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| Figure 12: Plots showing the relationship between hydrometeor trajectory angle (left) and wind speed (right) with leaf contact area, (top row) and the increase in leaf contact area, i.e., (bottom row). Simulated hydrometeor trajectory angle is measured as degrees from zenith. Simulated wind speed was calculated as a function of hydrometeor trajectory angle by rearranging [Equation 4](#eq-ta) and an observed event hydrometeor velocity of 0.9 m s-1. The solid lines (VoxRS) represent the mean leaf contact (top) or increase in leaf contact area (bottom) area observed from VoxRS across all grid cells for each forest plot and across all azimuth angles for a single zenith angle. The shaded area represents 1 standard deviation above and below the observed VoxRS mean. The dashed lines (Fitted) represent predictions from [Equation 10](#eq-lca-ac) (top) and [Equation 11](#eq-lca-inc) (bottom). The dotted lines (HP98) represent the predictions from Equation 10 in Hedstrom & Pomeroy (1998). A forested downwind distance of 100 m was used for the HP98 calculation. The line colour represents the forest plot, FT (black) and PWL (red) |

A function is proposed here that calculates plot scale leaf contact area, (-):

where, is the increase in leaf contact area from which is a function of the zenith angle (hydrometor trajectory) of interest. To estimate a non-linear least squares regression using a logistic function forced through the origin was fit to the FT and PWL observations (see dashed lines in bottom row of [Figure 12](#fig-lca-ht-ws)). The logistic function used predict as a function of is:

where is the maximum value of , is the x value of the sigmoid midpoint and is the logistic growth rate or steepness of the curve. Resulting coefficients for , and derived across the VoxRS observations from the PWL and FT forest plots were 0.947, 54.084 and 28.997 respectively. A logistic function was selected to model this relationship, as its shape was deemed most appropriate to represent the change in with trajectory angle. This choice reflects the observed slow increase in at near vertical trajectory angles. The logistic function also captures the non-linear increase at more horizontal trajectory angles, where snowflakes encounter more canopy area in the middle and lower section of individual trees. Additionally, the function effectively represents the gradual levelling off of as it approaches full coverage (value of one).

Simulated using [Equation 10](#eq-lca-ac) is shown in the dashed lines in the top row of [Figure 12](#fig-lca-ht-ws) and follows closely to the VoxRS observed plot wide mean . Model error statistics shown in [Table 3](#tbl-lca-mod-err) demonstrate that [Equation 10](#eq-lca-ac) performed well, with a mean bias and RMSE of 0.001 and 0.0054 respectively for PWL, and -0.0004 and 0.0079 for FT. In contrast, [Table 3](#tbl-lca-mod-err) reveals that the Hedstrom & Pomeroy (1998) method produced significantly less accurate estimates of , with a mean bias and RMSE of -0.201 and 0.233 respectively for PWL, and -0.260 and 0.324 for FT.

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| Table 3: Model error statistics calculated for the prediction of leaf contact area from trajectory angle using [Equation 11](#eq-lca-inc) (nls), using a linear function from the observations in this study (lm), and Equation 10 from Hedstrom & Pomeroy (1998). Mean bias is the difference in the model and observed values, MAE is the mean of the absolute error, RMS Error is the root mean squared error and r^2 is the coefficient of determination.   | Model | Plot | Mean Bias | MAE | RMS Error | R^2 | | --- | --- | --- | --- | --- | --- | | HP98 | FT | -0.0991 | 0.0991 | 0.1212 | 0.7136 | | HP98 | PWL | -0.0665 | 0.0767 | 0.0912 | 0.5045 | | nls | FT | 0.0004 | 0.0013 | 0.0016 | 0.9997 | | nls | PWL | 0.0006 | 0.0023 | 0.0028 | 0.9991 | |

## 4.5 Throughfall Model Performance

The performance of [Equation 9](#eq-lca-ip) in estimating interception efficiency and throughfall () was assessed at the plot scale for both FT and PWL. Measured values of from UAV-lidar averaged over each forest plot were used for each forest plot, measured at PWL station, measured at FT station, and measured at PWL station were used as inputs for this model. The constants required for this model were used from those derived in the previous section, including , height of wind within the canopy, and the constants used in [Equation 11](#eq-lca-inc).

Predicted values of observed and modelled interception efficiency and are shown in [Table 4](#tbl-vb-plot-err) along with corresponding error statistics. [Figure 13](#fig-event-tf) shows the vector based (vb) method, computed using [Equation 9](#eq-lca-ip) with adjusted for estimated hydrometeor trajectory angle, relatively good performance with estimates of 16.2 mm and 20.8 mm for the PWL and FT plots respectively, compared to observed of 16.6 mm and 22.1 mm respectively. This low difference in modelled and observed leads to the low bias of up to 1 mm between the two forest plots. The percent error in estimated is higher for the vector based model at FT 5.6% compared to 2.4% at PWL. An over estimate of interception efficiency may be attributed to a slight over sensitivity of [Equation 11](#eq-lca-inc) for the sparser canopy of FT compared to the denser PWL canopy. An overestimate of interception efficiency may be expected as the observations of interception efficiency may have been lower due to some unloading of snow over the March 13-14 snowfall event. If the trajectory angle is not accounted for (nadir) ~2 mm more throughfall is predicted as a result of increased snow interception in the vector based model for both forest plots which leads to a corresponding underestimate of interception efficiency for the nadir model.

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| Figure 13: Bar chart comparing the observed and modelled mean change in throughfall (𝚫 SWE, kg m⁻²) over the March 13-14 snowfall event averaged over forest plots FT and PWL. The ‘nadir’ data type used [Equation 9](#eq-lca-ip) but was not adjusted for trajectory angle and thus was used instead of , ‘obs’ corresponds to the UAV-lidar measured change in throughfall, and ‘vb’ is the change in throughfall predicted from the vector based (vb) model which uses [Equation 9](#eq-lca-ip) with adjusted for trajectory angle. The black horizontal dashed line shows the accumulated SWE (kg m⁻²) over the snowfall event to the PWL station open clearing. |

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| Table 4: Model error statistics for model estimates of snow interception efficiency (ip) and throughfall (tf) compared to measurements of ip and tf using UAV-lidar averaged over the FT and PWL forest plots. The ‘mod\_type’ column refers to the method used to estimate ip and tf. The vector based (vb) method utilized [Equation 9](#eq-lca-ip) with adjusted for trajectory angle. The nadir method also utilized [Equation 9](#eq-lca-ip) but was not adjusted for trajectory angle and thus was used inplace of . The obs\_val column contains measurements from UAV-lidar while the mod\_val column contains values from the respective mod\_type method. Bias was calculated as observed minus modelled, MAE is the absolute bias value, and Perc. Error is the percent error between predicted and observed values.   | plot | val\_name | mod\_type | obs\_val | mod\_val | bias | MAE | Perc. Error | | --- | --- | --- | --- | --- | --- | --- | --- | | FT | ip | vb | 0.22 | 0.26 | -0.04 | 0.04 | -19.25 | | FT | ip | nadir | 0.22 | 0.20 | 0.02 | 0.02 | 9.58 | | FT | tf | vb | 22.07 | 20.86 | 1.21 | 1.21 | 5.49 | | FT | tf | nadir | 22.07 | 22.68 | -0.60 | 0.60 | -2.73 | | PWL | ip | vb | 0.41 | 0.43 | -0.02 | 0.02 | -4.12 | | PWL | ip | nadir | 0.41 | 0.37 | 0.05 | 0.05 | 11.72 | | PWL | tf | vb | 16.64 | 16.15 | 0.48 | 0.48 | 2.91 | | PWL | tf | nadir | 16.64 | 18.01 | -1.37 | 1.37 | -8.26 | |

Maybe show table of modelled swe error at varying grid cell sizes using the model… ?

# 5. Discussion

To Add:

* hydrometeor velocity is another point of uncertainty not typically measured so would have to be assumed.
* wind speeds at lower heights align with Katsushima et al. (2023) results
* okay if the model slightly over predicts I/P as we havent taken into accont ablative processes which would likely be important over the march 13-14 snowfall event.

At the point scale, relatively little influence of meteorology on interception efficiency was found in the observations collected from this discontinuous subalpine forest. A slight increase in interception efficiency was observed at the SCLs with increasing wind speeds below 1.5 m s-2 and canopy snow loads below 7 kg m-2 and is attributed to an associated increase in the [Figure 7](#fig-lai-met-ip). At wind speeds above 2 m s-1, interception efficiency was observed to decline by a maximum of 0.1 (-) and could be attributed to increasing hydrometeor velocity leading to increased bouncing of snowflakes off branches and wind-induced unloading (Katsushima et al., 2023; Lumbrazo et al., 2022; Roesch et al., 2001). The increase in interception efficiency up to canopy snow loads of 7 kg m-2 and then subsequent decline is attributed to the position of the SCLs within forest gaps. Timelapse imagery showed that branches surrounding the SCLs compressed at snow loads above 7 kg m-2 reducing the canopy coverage above the instruments. This is similar to the theory proposed by Satterlund & Haupt (1967) that interception efficiency increases as the canopy fills with snow bridging gaps in the canopy, while later declining due to branch bending and decreased canopy coverage. Hedstrom & Pomeroy (1998) and Storck et al. (2002) did not observe this initial increase, but are consistent in declining interception efficiency at high snow loads. The observations presented in [Figure 7](#fig-lai-met-ip), differ from the Satterlund & Haupt (1967), Hedstrom & Pomeroy (1998), Storck et al. (2002) and Moeser et al. (2015) theories, in that the decline in interception efficiency at high canopy snow loads was at a rate much slower than has been observed by these studies (see Figure 6 in Cebulski & Pomeroy (2024)). The strong exponential decline in interception efficiency observed with increasing event snowfall in Satterlund1967, Hedstrom & Pomeroy (1998), Storck et al. (2002) and Moeser et al. (2015) may be a result of increased unloading rates as branches compress with heavy snow loads. The longer duration between site visits in (Hedstrom & Pomeroy, 1998; Moeser et al., 2015; Satterlund & Haupt, 1967) increase the likelihood of canopy snow ablation in their throughfall measurements compared to the automated measurements in this study. This potential inclusion of canopy snow ablation within the interception parameterizations provided in (Hedstrom & Pomeroy, 1998; Moeser et al., 2015; Satterlund & Haupt, 1967; Storck et al., 2002) may lead to double counting of unloading when combined with an additional unloading parameterizations in models that are not calibrated to account for this.

The observations presented in this study deviate from the relationships outlined in Hedstrom & Pomeroy (1998) and Storck et al. (2002) which suggested either a positive (Storck et al., 2002) or negative (Hedstrom & Pomeroy, 1998) association of air temperature with the canopy snow storage capacity (see fig. X Cebulski & Pomeroy (2024)). Specifically, the increase in canopy snow load with increasing snowfall shown in [Figure 6](#fig-scl-w-sf), did not show evidence of reaching a canopy snow storage capacity. The ablation of canopy snow at higher canopy snow loads prevented the observation of a maximum canopy snow storage capacity. Lundquist et al. (2021) reported improved simulation of subcanopy snow accumulation without the use of a maximum canopy snow storage capacity when combined with ablation process representations for canopy snow melt, sublimation, wind-induced unloading and temperature induced unloading. However, Lehtonen et al. (2016) note that in northern Finland heavy canopy snow loads have been observed to continue increasing until stem breakage, under conditions favourable for the formation of significant rime-ice accretion and limited ablation. While further research is required to understand the canopy snow load required to cause stem breakage across different tree species, additional research on canopy snow ablation processes could better represent the decline in interception efficiency with increasing canopy snow loads that has been observed by Satterlund & Haupt (1967), Schmidt & Pomeroy (1990), Hedstrom & Pomeroy (1998) and Moeser et al. (2015).

Empirical evidence to support the theory of increased in canopy contact area with increased wind speed (Hedstrom & Pomeroy, 1998) has not been provided in the literature. Measurements of interception efficiency collected across two forest plots in this study showed a large fraction of snow intercepted on the lee side of individual trees as shown in [Figure 8](#fig-lidar-tf-ip) due to predominately non-vertical hydrometeor trajectory angles. A greater footprint of increased interception efficiency was observed across the PWL study site and is attributed to the large difference in canopy coverage between the two plots rather than localized wind flow patterns. Despite the difference in interception efficiency observed across the two forest plots, a similar zone of high correlation between and interception efficiency was found in the hemisphere plots shown in [Figure 10](#fig-hemi-ip-cc). Using the average wind speed observed at FT station, [Equation 4](#eq-ta) predicted a trajectory angle that was more horizontal compared to the observations from the hemisphere plots. This may be partially explained by three factors, 1) the height of the wind speed measurement at 4.2 m may be higher than the dominant wind flow important for controlling hydrometeor trajectory and subsequent interception (i.e., the conical shape of needleleaf trees have a larger surface area closer to the ground), 2) extrapolating wind speed measured within sparse canopy (FT Station) to regions characterized by higher stem density across the study site, where wind speed may have been lower leading to more vertical trajectory angles, and 3) the theory proposed in [Equation 4](#eq-ta) assumes a linear hydrometeor trajectory, and does not consider non-linear patterns such as wind flow wrapping around tree elements, turbulent flow, or differences in wind speed with height. Future use of [Equation 4](#eq-ta) should therefore utilize wind speeds scaled down to a lower height above ground using [Equation 5](#eq-uz), such as 1/3 the canopy height as suggested by Katsushima et al. (2023). Wind speed and direction were shown to be important factors influencing the portion of the hemisphere that governed snow accumulation [Figure 10](#fig-hemi-ip-cc). However, at the forest plot scale, directional differences are expected to be negligible compared to the increase in leaf contact area with trajectory angle. At this scale, [Equation 11](#eq-lca-inc), which uses trajectory angle alone, could be sufficient to determine .

This study, in agreement with previous research (Calder, 1990; Lundquist et al., 2021), did not observe an association between canopy snow load and interception efficiency. These findings challenge the theoretical basis of the existing snow interception parameterizations (Hedstrom & Pomeroy, 1998; Moeser et al., 2015; Satterlund & Haupt, 1967; Storck et al., 2002), and suggest these models may need revision. To address this a new snow interception parameterization, [Equation 9](#eq-lca-ip), is presented which calculates interception efficiency as a function of and . This new parameterization allows for canopy snow loading processes to be isolated from canopy snow ablation processes following suggestions in Cebulski & Pomeroy (2024) to be more consistent with the rainfall interception literature (Valante et al., 1997). [Equation 9](#eq-lca-ip) differs only slightly from the original Hedstrom & Pomeroy (1998) parameterization (see Equation 6 in Hedstrom & Pomeroy (1998)), in that it does not calculate interception efficiency as a function of canopy snow load and from the Storck et al. (2002) parameterization who found interception efficiency to be a constant. The theoretical basis of the value in [Equation 9](#eq-lca-ip) is that the association between and interception efficiency, as shown in [Figure 11](#fig-lca-vs-ip), does not follow a 1:1 line as snow flakes may bounce off the canopy elements. Some minor redistribution of snow during between UAV-lidar scans may have lowered the value observed in this study and in reality may be slightly higher if considering measurements of interception efficiency without unloading. Although, no relationship was found between interception efficiency and air temperature in this study [Figure 7](#fig-lai-met-ip), Lundquist et al. (2021) discuss that the cohesion and adhesion of individual snowflakes to canopy elements is a function of air temperature and may influence the value. This new snow interception parameterization, is also consistent with Lundquist et al. (2021) who showed success using a constant interception efficiency value for a point location. However, since is a canopy metric typically available across the globe, [Equation 9](#eq-lca-ip), when combined with [Equation 10](#eq-lca-ac) and [Equation 11](#eq-lca-inc), provides a way to determine interception efficiency spatially across the landscape. This method is also similar to the rainfall interception literature, which calculate throughfall as a function of (i.e., Valante et al., 1997). However, in Valante et al. (1997), rainfall interception is assumed to be completely efficient (i.e., = 1). Moreover, the use of in Valante et al. (1997) to calculate rainfall interception is not adjusted for hydrometeor trajectory angle. While the higher terminal fall velocity of rainfall compared to snow would result in a smaller sensitivity of to wind speed for rainfall [Figure 5](#fig-ws-vs-ta), this still may result in an underestimate of rainfall interception (Herwitz & Slye, 1995; Van Stan et al., 2011). The large sensitivity of to hydrometeor trajectory angle and the associated implications for subcanopy snow accumulation shown in this study, resulting from relatively common wind speeds of 1-2 m s-1, suggests that this may be an important process to consider, especially in snow dominated basins.

A substantial increase in plot scale was shown as a result of increasing hydrometeor trajectory angle which led to an increase in the number of contacts with needleleaf canopy elements. Compared to this, the influence of canopy snow load on interception efficiency at the point scale in [Figure 7](#fig-lai-met-ip) was relatively small. The negligible change in observed at the plot scale after a large snowfall event suggests incorporating canopy snow load in interception efficiency parameterizations may not be necessary for this study site. This is interpreted to be due to compensatory effects, where snow load may increase the for vertical zenith angles in grid cells beneath the canopy as snow bridges gaps in the canopy elements. However, branch bending may also lead to a decrease in for grid cells within gaps between the canopy or for non-vertical trajectory angles. Staines & Pomeroy (2023), showed a slight increase in between snow-off conditions from a single UAV-lidar scan compared to snow-on conditions derived from a combination of three UAV-lidar scans. The higher forest density in the Staines & Pomeroy (2023) study resulted in more of their study area beneath canopy elements, and was not as influenced by branch bending. This may have resulted in a slightly higher influence of snow load on in the Staines & Pomeroy (2023) study, compared to negligible effect reported here between the March 13 and 14 UAV-lidar surveys. Still, the increase in resulting from snow load in Staines & Pomeroy (2023) was smaller compared to the substantial rise in due to trajectory angle. An existing method proposed in Hedstrom & Pomeroy (1998) to scale canopy coverage with wind speed failed to reproduce the observations presented in [Figure 12](#fig-lca-ht-ws). A new method is proposed which uses logistic function to calculate as a function of and . There was only a slight improvement in the non-linear formulation of [Equation 11](#eq-lca-inc) compared to the linear equation, however, the non-linear function provided a better balance between the two forest plots as shown in [Figure 12](#fig-lca-ht-ws), and has a better theoretical justification. Further work is required to refine the relationship proposed in [Equation 11](#eq-lca-inc) across a range of tree species and densities, determine how to calculate the canopy snow storage capacity, reassess canopy snow ablation parameterizations of the new snow interception routine.

# 6. Conclusions

* New observations of snow interception collected at both high-frequency and fine-scale resolutions provide insights on the applicability of existing theories to this research site.
* A canopy snow load capacity was not observed for these observations and thus additional observations of canopy snow load for larger snowfall or rime-ice events are required to determine a canopy snow load capacity.
* No association of air temperature, relative humidity, hydrometeor velocity, or hydrometeor diameter on interception efficiency was observed from the high-frequency point scale measurements. These measurements also showed interception efficiency increased slightly with wind speed and low-moderate canopy snow loads as a result of increasing the leaf contact area. A slight decline in interception efficiency at higher canopy snow loads was observed at the point scale and was attributed to branch bending reducing the canopy coverage of the instruments. The absence of a strong association between air temperature or canopy snow load with interception efficiency challenges the theoretical foundation of most existing snow interception parameterizations.
* At the forest plot scale, UAV-lidar measurements showed leaf contact area is the main factor governing the fraction of intercepted snowfall at a particular site. At this scale the decline in interception efficiency in forest gaps due to branch bending appeared to be balanced by the increase in leaf contact area within the canopy due to increased snow load. Snow accumulation and canopy structure metrics from a wind-driven snowfall event revealed canopy structure metrics adjusted for trajectory angle provided an improved predictor of interception efficiency compared to nadir canopy coverage.
* Leaf contact area was observed to double for wind speeds of 1 m s-1 in the discontinuous subalpine forest in this study. The effect of wind on leaf contact area can have large implications for the amount of snow intercepted in the canopy. An existing theoretical relationship failed to represent the increase in leaf contact area with wind speed at this site.
* A new snow interception parameterization has been presented which calculates initial interception, before canopy snow ablation, as a function of snowfall rate and leaf contact area. The formulation of this parameterization as a function of canopy structure is consistent with the rainfall interception literature and other recent observations of snow interception.
* A second equation is proposed to estimate the increase in leaf contact area from nadir canopy coverage as a function of hydrometeor trajectory angle. This relationship was shown to follow a relatively similar relationship at two forest plots with differing canopy structure and was represented by a single parameterization.
* Good performance of this updated snow interception parameterization was shown in this subalpine forest, but further validation should be conducted in a range of climates, forest species and structures. Caution should be taken in using this updated interception routine with existing canopy snow ablation parameterizations as they were developed using earlier snow interception routines that also included ablative processes. Future work will involve revising canopy snow ablation routines to work with this new snow interception routine.

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# 8. Data Availability

The authors declare there are no competing interests.

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