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

**Authors:**

A. Cebulski1 (ORCID ID - 0000-0001-7910-5056)

J.W. Pomeroy1 (ORCID ID - 0000-0002-4782-7457)

1Coldwater Laboratory, University of Saskatchewan, Canmore, Canada

**Corresponding Author:** A. Cebulski, alexcebulski@gmail.com

(**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 include inherently coupled accumulation and ablation processes, leading to difficulty in diagnosing processes and adding uncertainty to simulations when incorporated as canopy accumulation routines in models that already account for canopy snow ablation. This study evaluates the theory underpinning these parameterizations and proposes a new snow interception routine using data from two subalpine forest plots in 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 with interception efficiency 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 non-vertical hydrometeor trajectories significantly reduced throughfall depths across both forest plots. Prediction of interception efficiency for this event improved drastically when adjusted for hydrometeor trajectory angle based on a wind speed at one-third of the canopy height. Snow-leaf contact area showed high sensitivity to wind speed, increasing by up to 95% with a 1 m s-1 wind speed. The study proposes two new equations which model snow interception efficiency as a function of snow-leaf contact area adjusted for hydrometeor trajectory angle. This new parameterization successfully estimated interception efficiency for a snowfall event for the two forest plots in this study. By removing canopy snow ablation processes, this new model should offer improved performance in prediction of sub-canopy snow accumulation when combined with canopy snow ablation parameterizations.

**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 forest canopies (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 increase snowmelt runoff but do not always commensurately increase spring streamflow (Golding & Swanson, 1978; Harpold et al., 2020; Pomeroy et al., 2012; Troendle, 1983). This may be due to increased ablation rates when forest cover is reduced, desynchronization of snowmelt, and sub-surface hydrology interactions (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 from the canopy (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 the rate of unloading (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 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 distinguish interception from ablation processes. As a result, existing parameterizations for snow interception are sometimes coupled to ablation processes (e.g., Hedstrom & Pomeroy, 1998; Katsushima et al., 2023) and may not be compatible when combined with additional ablation process representations in uncalibrated models (Clark et al., 2020; Verseghy, 2017; Wheater et al., 2022).

The coupling of ablation 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 ablation 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 between maximum canopy snow load and air temperature (Cebulski & Pomeroy, 2024). Lundquist et al. (2021) found improved subcanopy snowpack simulations when they omitted the maximum canopy snow load from Hedstrom & Pomeroy (1998), from a model otherwise linked to a complete representation of canopy snow ablation processes. This, combined with studies which have not found a maximum canopy snow load (Calder, 1990; Katsushima et al., 2023; Storck et al., 2002), and the attribution of decreased interception at higher canopy snow loads to ablation processes rather than reduced canopy structure due to branch bending alone by (Hedstrom & Pomeroy, 1998; Moeser et al., 2015; Satterlund & Haupt, 1967; Schmidt & Gluns, 1991), suggests the maximum canopy snow load may be much higher than existing models predict. This leads to uncertainty in the role of the maximum canopy snow load in snow interception and subsequent unloading. It may be beneficial to reformulate canopy snow ablation parameterizations as a function of canopy snow load rather than limiting initial interception for consistency with current rainfall interception theory for considering transitional rainfall-snowfall interception (e.g., Valante et al., 1997). Avoiding using the maximum canopy snow load as a parameter in algorithms might also improve interception calculations in regions that are prone to rime-ice formation (Lumbrazo et al., 2022) which can lead to heavy snow loads causing stem breakage (Lehtonen et al., 2014, 2016).

It remains uncertain how processes understanding developed at the branch and tree scale like bridging of gaps in canopy elements (Satterlund & Haupt, 1967) and branch bending (Pomeroy & Gray, 1995; Schmidt & Gluns, 1991) influence snow accumulation at the forest plot scale. 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; Mahat & Tarboton, 2014), as empirical support for this relationship is lacking and it also exhibits a relatively low sensitivity (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 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 spatial and temporal resolution measurements of subcanopy snow accumulation events with minimal ablation 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 ablation processes can be assumed negligible, the canopy snow load, (kg m-2) can be estimated as a mass balance:

where is the snowfall rate (kg m-2 s-1) and is the throughfall rate (kg m-2 s-1). This method avoids the influence of sublimation losses or drip from weighed tree lysimeters.

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, .

[Figure 1](#fig-ws-vs-ta) shows the increase in calculated using [Equation 3](#eq-ta) with differing hydrometeor terminal fall velocities of 0.5, 1, and 1.5 m s-1 and a horizontal velocity equal to wind speed ranging from 0-20 m s-1.

|  |
| --- |
| Figure 1: Plot showing the relationship of hydrometeor trajectory angle (departure from zenith) with increasing horizontal velocity from [Equation 3](#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). |

## 2.3 Canopy Wind Speed Profile

Wind speed increases with height above the ground surface following a logarithmic relationship:

where is average wind speed, is the friction velocity (m s-1), is the height above ground (m), is the displacement height (m), is the roughness length of momentum (m), and is the von Kármán Constant (-).

# 3. Data and Methods

## 3.1 Study Site

This study was conducted at Fortress Mountain Research Basin (FMRB), Alberta, Canada, -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 was 1045 kg m-2, with the peak annual snow water equivalent (SWE) reaching 465 kg m-2, typically occurring in late April. The PWL and FT forest plots include discontinuous stands of 70% subalpine fir (Abies lasiocarpa) and 30% Engelmann spruce (Picea engelmannii) (Langs et al., 2020). The PWL plot is located 120 m to the northwest of FT station and contains a forest clearing with a diameter of ~12 m and is surrounded by a more closed canopy. The canopy coverage of the PWL and FT forest plots is 0.51 and 0.29 respectively. 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 forest of the FT plot is characterized by discontinuous canopy without artificial clearings. In August of 1936 the majority of vegetation in FMRB burned during a large forest fire that affected most of the Kananaskis Valley (Fryer & Johnson, 1988). Following the fire, the forest within the the PWL and FT forest plots has naturally regenerated, though some trees have been removed for road clearing and creation of a snow study plot.

|  |
| --- |
| 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. |

## 3.2 Meteorological Measurements

Measurements of air temperature and relative humidity (Vaisala model HMP155A), wind speed and direction (RM Young model 86000 2-D ultrasonic anemometer) were made 4.3 m above the ground at the FT station ([Figure 2](#fig-site-map)). Wind speed measurements from a 3-cup anemometer (Met One model 014A), installed at adjacent to the 2-D ultrasonic anemometer, were used for gap filling wind speed. Additional wind speed measurements were collected by two 3-D sonic anemometers (Campbell Scientific CSAT3) installed at at 3 m and 13.5 m above the ground at FT station. A wind speed profile was developed for FT station using [Equation 4](#eq-log-wind-profile). To determine the displacement height and roughness length parameters, an optimization function “optim” from the stats R package (R Core Team, 2024) was used that minimized the squared error between modelled and observed wind speeds. The parameters for the wind speed profile include a roughness length of 0.50 m, displacement height of 0.58m. At PWL station, the snowfall rate was measured by an Alter-shielded OTT Pluvio weighing precipitation gauge 2.6 m above ground, corrected for undercatch following phase correction by Harder & Pomeroy (2013) and catch efficiency by Smith (2007). Wind speed for undercatch correction was measured by a 3-cup anemometer (Met One model 014A) at a height of 2.6 m at PWL station. An optical disdrometor (OTT Parsivel2) provided measurements of hydrometeor particle size and vertical velocity. All measurements were recorded at 15-min intervals using Campbell Scientific Canada dataloggers, except the Parsivel2 which was recorded at 1-minute intervals by an onsite computer.

## 3.3 Lysimeter Data

Three subcanopy lysimeters (SCLs) were installed surrounding the FT Station to provide 15-minute interval measurements of sub-canopy snowfall (see locations in [Figure 2](#fig-site-map)). The SCLs consisted of a plastic horse-watering trough with an opening of 0.9 m2 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 weight was scaled to kg m-2 by dividing by the cross-sectional area of the SCL opening. Interception efficiency was quantified at 15-minute intervals using [Equation 1](#eq-dwdt-ode) and [Equation 2](#eq-ip). The calculation incorporated the measurements of obtained from the SCLs and recorded by the the PWL snowfall gauge. This analysis was conducted over a dataset comprising 26 distinct snowfall events. Timelapse imagery, mass change on a weighed tree lysimeter “hanging 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 snowfall events. When canopy snow ablation processes could be considered negligible, the SCLs provided measurements of (see method described in Cebulski & Pomeroy, 2024). 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).

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 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 (-) | | --- | --- | --- | | Sparse | 1.59 | 0.73 | | Mixed | 1.86 | 0.78 | | Closed | 2.11 | 0.82 | |

The 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) each year to record the weight of the tree. The bottom of the tree was sealed with pruning tar to restrict sap loss. The base of the tree was attached to a support system that allows for vertical movement but limited abrupt horizontal movements and prevented spinning. The weight of snow intercepted on the weighed tree 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 locations 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) from snow pits. 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 period 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 was observed, 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). Areas 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 developed 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 trajectories. 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, four metrics comparing observed and modelled values were calculated: mean bias, mean absolute error (MAE), root mean square error (RMSE), and the coefficient of determination (R2). Kozak & Kozak (1995) noted, the default R2 value provided for least squares models forced through the origin by many statistical packages can be misleading. Therefore, these R2 values were adjusted using Equation 10 in Kozak & Kozak (1995) and two statistical tests as described by Kozak & Kozak (1995) were used to verify whether a no-intercept model (forced through the origin) was appropriate for this data compared to a with-intercept model. 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 (R Core Team, 2024). 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 3](#fig-scl-w-sf) plots canopy snow load against cumulative snowfall, over 26 snowfall events using the three SCLs and the PWL snowfall gauge. The meteorology of each snowfall event is summarized in [Table 2](#tbl-sf-event-met) and shows air temperature over these periods ranged from a minimum of -24.4791172 to a maximum of -24.4791172°C. Wind speeds ranged from a minimum of 0.0251858 to a maximum of 0.0251858. Canopy snow load was observed in [Figure 3](#fig-scl-w-sf) to increase linearly with increasing snowfall without evidence of reaching a maximum. Variation in the slope of each line in [Figure 3](#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. [Figure 4](#fig-scl-ip-avg-event) shows mean event air temperature had a significant (*p* < 0.05) negative weak association with interception efficiency, while the other two troughs displayed insigificant relationships (*p* > 0.05). Cumulative event snowfall had a consistent negative association with cumulative snowfall, however the relationships were insignificant for all three troughs (*p* > 0.05). Event mean wind speed exhibited a positive association with interception efficiency for the sparse (*p* > 0.05) and closed (*p* < 0.05) SCLs. A negative insigificant association was observed for the mixed SCL (*p* > 0.05). The opposing relationship of wind speed and interception efficiency between the SCLs can be explained as the mixed SCL has an opening in the canopy towards the prevailing wind direction, shown in [Figure 6](#fig-wind-rose), thus increasing the amount snowfall entering the sub-canopy. For the closed and sparse SCLs 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 absence of canopy snow load measurements in [Figure 3](#fig-scl-w-sf) for certain troughs during specific events was caused by damage to the subcanopy lysimeter wiring due to animals and heavy snow loads.

|  |
| --- |
| Figure 3: 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). |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 2: Meteorological statistics for the 26 snowfall events.   | Start Date | Duration (Hrs) | Air Temperature (°C) | | | Wind Speed (m/s) | | | Interception Efficiency (-) | | | Total Snowfall (mm) | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | | 2021-12-23 | 14.50 | −6.2 | −5.3 | −4.6 | 0.6 | 3.1 | 4.6 | 0.7 | 0.8 | 1.0 | 21.7 | | 2022-01-02 | 145.00 | −15.9 | −10.6 | −5.8 | 0.2 | 1.9 | 4.2 | 0.1 | 0.7 | 1.0 | 32.9 | | 2022-01-17 | 11.50 | −14.8 | −7.8 | −0.8 | 0.2 | 1.1 | 1.8 | 0.0 | 0.6 | 1.0 | 12.9 | | 2022-01-31 | 25.75 | −24.5 | −12.1 | −6.4 | 0.1 | 1.0 | 1.7 | 0.2 | 0.7 | 1.0 | 9.1 | | 2022-02-14 | 2.25 | −9.9 | −9.0 | −8.5 | 0.4 | 0.8 | 1.2 | 0.2 | 0.5 | 0.8 | 1.7 | | 2022-02-19 | 8.25 | −4.7 | −3.2 | −2.5 | 1.3 | 2.3 | 3.6 | 0.3 | 0.6 | 0.9 | 11.1 | | 2022-03-01 | 54.75 | −8.3 | −5.4 | −1.0 | 0.1 | 1.0 | 3.1 | 0.4 | 0.8 | 1.0 | 9.9 | | 2022-03-07 | 10.25 | −12.5 | −8.6 | −4.4 | 0.3 | 0.8 | 1.7 | 0.3 | 0.7 | 1.0 | 9.5 | | 2022-03-14 | 29.25 | −2.7 | −2.1 | −0.8 | 1.0 | 1.6 | 2.9 | 0.2 | 0.6 | 0.9 | 8.4 | | 2022-03-19 | 2.75 | −3.1 | −2.8 | −2.5 | 0.0 | 0.7 | 1.3 | 0.3 | 0.5 | 0.6 | 6.6 | | 2022-03-23 | 6.00 | −7.9 | −5.3 | −0.9 | 0.8 | 1.2 | 1.8 | 0.4 | 0.6 | 0.9 | 1.6 | | 2022-04-04 | 1.75 | −3.5 | −2.9 | −2.1 | 0.6 | 1.0 | 1.9 | 0.0 | 0.4 | 0.6 | 3.4 | | 2022-04-18 | 14.50 | −5.2 | −4.0 | −2.7 | 0.4 | 1.1 | 1.9 | 0.1 | 0.5 | 0.9 | 7.4 | | 2022-04-22 | 18.75 | −2.8 | −1.8 | −0.5 | 0.4 | 0.8 | 1.2 | 0.1 | 0.5 | 1.0 | 9.8 | | 2022-05-09 | 5.00 | −4.9 | −4.3 | −3.2 | 0.1 | 0.4 | 0.9 | 0.2 | 0.5 | 0.9 | 8.1 | | 2022-05-19 | 19.25 | −4.9 | −2.1 | 0.3 | 0.1 | 0.4 | 0.9 | 0.2 | 0.6 | 0.9 | 7.1 | | 2022-06-13 | 15.00 | −1.1 | −0.3 | 0.6 | 0.1 | 0.1 | 0.4 | 0.0 | 0.5 | 0.9 | 45.3 | | 2022-12-27 | 7.00 | −3.0 | −2.7 | −1.9 | 0.6 | 1.1 | 1.8 | 0.2 | 0.5 | 0.9 | 4.5 | | 2023-01-27 | 16.00 | −11.5 | −7.3 | −4.5 | 0.6 | 0.9 | 1.2 | 0.1 | 0.5 | 0.8 | 10.4 | | 2023-02-19 | 31.00 | −14.3 | −9.5 | −6.3 | 0.2 | 0.8 | 1.4 | 0.2 | 0.7 | 1.0 | 18.1 | | 2023-02-26 | 2.00 | −9.2 | −8.4 | −6.6 | 0.2 | 1.0 | 2.1 | 0.3 | 0.5 | 1.0 | 5.4 | | 2023-03-13 | 21.00 | −8.9 | −3.6 | −0.1 | 0.3 | 1.3 | 2.2 | 0.0 | 0.5 | 1.0 | 27.4 | | 2023-03-24 | 15.50 | −7.9 | −5.7 | −3.5 | 0.1 | 0.5 | 1.2 | 0.1 | 0.4 | 0.7 | 23.8 | | 2023-04-01 | 13.00 | −8.9 | −7.7 | −4.7 | 0.1 | 0.6 | 1.4 | 0.4 | 0.6 | 0.8 | 11.4 | | 2023-04-10 | 8.25 | −1.1 | −0.5 | 0.3 | 0.1 | 0.3 | 1.0 | 0.2 | 0.4 | 0.6 | 18.0 | | 2023-05-08 | 1.00 | 0.2 | 0.6 | 1.0 | 0.4 | 0.6 | 0.8 | 0.6 | 0.6 | 0.7 | 3.5 | |

|  |
| --- |
| Figure 4: Scatter plots showing the mean air temperature and wind speed and total cumulative snowfall versus the mean interception efficiency measured by 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). A linear regression line fit to the data is shown by the solid coloured lines and the corresponding adjusted r squared value. Significant relationships (p < 0.05) are marked by an asterix beside the R2 value. |

[Figure 5](#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. Panel A in [Figure 5](#fig-lai-met-ip) shows that 15-minute average air temperature measurements has a very low correlation (R2 < 0.032) with interception efficiency for all three SCLs with significant relationships (*p* < 0.05) only for the sparse and mixed troughs. The average interception efficiency observed within air temperature bins also does not visually exhibit any systematic trend. However, a significantly greater median interception efficiency (*p* < 0.05) was found for air temperatures below -6 °C compared to colder air temperatures using non-parameteric Wilcoxon signed rank test.

|  |
| --- |
| Figure 5: 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 kg m-2 hr-1, throughfall rate > 0.05 kg m-2 hr-1 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. |

Panel B in [Figure 5](#fig-lai-met-ip) shows that wind speed measured at FT Station had a slightly stronger correlation with interception efficiency with R2 ranging between 0.04 and 0.09 (*p* < 0.05 for all three SCLs) compared to the association with air temperature. The association between wind speed and interception efficiency was observed to be positive for the sparse and closed SCLs, while the mixed SCL exhibited a negative association. The opposing trend observed for the closed and sparse SCLs compared to the mixed SCL is consistent with the trend observed in [Figure 4](#fig-scl-ip-avg-event) for the event means and is also attributed to a change in snow-leaf contact area with shifting hydrometeor trajectories as a result of changing wind speed. 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 closed and sparse forest SCLs respectively ([Figure 5](#fig-lai-met-ip), B). The mixed SCL declined from 0.59 to 0.45 for the same range in wind speed bins. A comparison interception efficiency between 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) median interception efficiency compared to the low wind speed group for the closed and sparse SCL. Conversely, the Wilcoxon test showed the mixed SCL had significantly higher (*p* < 0.05) median interception efficiency for the low wind speed group.

|  |
| --- |
| Figure 6: Wind rose over all periods of snowfall with minimal unloading. |

[Figure 5](#fig-lai-met-ip), panel C shows canopy snow load, measured at the beginning of each timestep, shows a relatively weak significant negative relationship between the 15-minute observations (R2 < 0.4, *p* < 0.05) for the closed and sparse SCLs and a non-significant relationship was observed for the mixed SCL. The binned data show a small increase in interception efficiency was observed for all three troughs between canopy snow loads of 0 kg m-2 to 7 kg m-2. This was followed by a gradual decline in interception efficiency for snow loads greater than 7 kg m-2 with the closed and sparse SCL ([Figure 5](#fig-lai-met-ip), C). The interception efficiency measured by the mixed SCL also declines above 7 kg m-2 before increasing again around 16 kg m-2 and then declines again to a minimum interception efficiency of 0.39. A comparison of low (< 10 kg m-2) and high (> 10 kg m-2) 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.

## 4.2 The influence of forest structure on snow interception

UAV-lidar measurements of throughfall and canopy structure metrics provide insights on how the forest canopy influenced subcanopy snow accumulation during the March 13-14 snowfall event. This event totaled 28.7 kg m-2 of snowfall at PWL station 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 1.27 m s-1 and direction of 188° were observed 4.2 m above the ground at FT Station. UAV-lidar measurements of throughfall shown in [Figure 7](#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 kg m-2 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.

[Figure 7](#fig-lidar-tf-ip) shows the spatial distribution of throughfall and interception efficiency at the PWL and FT forest plots. Reduced throughfall and 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 7](#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.

|  |
| --- |
| Figure 7: 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). |

[Figure 8](#fig-hemi-ip-cc) presents two hemisphere plots which illustrate the correlation between and interception efficiency at a 0.25 m horizontal grid cell resolution over differing azimuth and zenith angles for both the FT and PWL forest plots. These plots demonstrate a strong linear 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 8](#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°. 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 believed to result from non-vertical hydrometeor trajectories. At near-nadir zenith angles, [Figure 8](#fig-hemi-ip-cc) illustrates slightly lower . In addition to the inclined hydrometeor trajectories, this may be influenced by reduced UAV-lidar returns, as shown in [Figure 7](#fig-lidar-tf-ip), and higher percent error proximal to the trunks of individual trees due to reduced throughfall depths. However, this limitation does not significantly alter the interpretation of the results.

|  |
| --- |
| Figure 8: 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 9](#fig-lca-vs-ip) shows that the correlation between 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°). The strong association suggests that adjusted is a useful predictor of interception efficiency, before ablation. For the vector-based model, adjusted was calculated using the VoxRS dataset corresponding to the azimuth range and zenith angle with the highest for each plot as 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.

The Nadir linear regression model provides a good overall fit to the observed data and closely follows the 1:1 line in [Figure 9](#fig-lca-vs-ip), with a value of 0.95 and 0.99 for the PWL and FT plot respectively. 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. After the Kozak & Kozak (1995) adjustment a negative R2 value for the PWL plot was determined. Some of the scatter observed in the Nadir model shown in [Figure 9](#fig-lca-vs-ip) 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 7](#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 7](#fig-lidar-tf-ip). This later explanation explains the non-linear relationship observed for the PWL Nadir model in [Figure 7](#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 reduced the fraction of snowfall that contacted the canopy that was intercepted.

Model error statistics are presented in [Table 3](#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 derived the values used in this analysis are rarely available and thus more accessible methods to obtain a proxy of must be obtained if [Equation 8](#eq-lca-ip) is to be employed in earth system models.

|  |
| --- |
| Figure 9: 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 fitted to the PWL (red) and FT (black) data and the light grey dotted line shows a 1:1 line. The R2 values for the four different models are shown in the upper right of each panel calculated following the methods outlined in Kozak & Kozak (1995). |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 3: Model error statistics provided for predictions of interception efficiency using [Equation 8](#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 The dominant trajectory angle for a snow interception event

A logarithmic wind speed profile shown in [Figure 10](#fig-wind-profiles) provided a good fit to the observed wind speed over the event and shows the Cionco (1965) exponential function was not appropriate for the sparse canopy surrounding FT station. The friction velocity observed over the March 13-14 event was estimated to be 0.37 m s-1 by rearranging [Equation 4](#eq-log-wind-profile) to solve for friction velocity using the site derived roughness length and displacement height values and the mean mean wind speed observed at FT Station at 4.2 m. This resulted in a mean event friction velocity of 0.37 m s-1. The heavy snowfall over this event covered the two eddy covariance systems at FT station with snow limiting wind speed measurements to test this wind speed profile at different heights or provide a measurement of friction velocity for this event.

[Figure 10](#fig-wind-profiles) shows predicted hydrometeor trajectory angles at varying heights, calculated using [Equation 3](#eq-ta) and the mean observed hydrometeor terminal velocity observed over the event of, 0.9 m s-1. An average wind speed of 1.63 m s-1 and direction of 188° was calculated by integrating the wind speed from the surface to the mean canopy height of FT plot. The corresponding trajectory angle, calculated using [Equation 3](#eq-ta), from this integrated wind speed was ft\_mean\_wind\_prof\_integral$traj\_angle |> round(2)°. This estimated trajectory angle is much higher than the trajectory angle closer to 20° observed in [Figure 8](#fig-hemi-ip-cc). Based on the wind speed profile in [Figure 10](#fig-wind-profiles) a trajectory angle of around 20° would have resulted from a mean wind speed of 0.36 m s-1 and 0.34 s-1 and a height above the snowpack of 1.32 m and 1.3 m for PWL and FT respectively.

Based on the event average snowpack depth at FT station of 1.47 m, this corresponds to a height above the ground that is 2.79 m and 2.77 m for PWL and FT respectively and fraction of the mean canopy height of 0.27 m and 0.39 as a result of the differing tree heights within two plots. This corresponds to roughly one-third the canopy height, based on an average of the two forest plots, 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.

|  |
| --- |
| Figure 10: Wind speed profile fit to roughness length and displacement height parameters derived from anemometors at 3, 4, and 15 m above ground at FT station over two years and friction velocity observed over the March 13-14th snowfall event. The red triangle shows the mean observed wind speed at 4.2 m measured at FT station over the March 13-14 snowfall event. |

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

[Figure 11](#fig-lca-ht-ws) shows that , measured from VoxRS prior to snowfall on March 13th, demonstrates a positive relationship with the simulated hydrometeor trajectory angle. The standard deviation in VoxRS measured , illustrated by the shaded area in [Figure 11](#fig-lca-ht-ws) exhibits the large range in values for individual grid cells across each forest plot. Despite this large scatter, a systematic increase in the plot mean results from a rise in the number of canopy elements for more horizontal portions of the hemisphere, when averaged across each forest plot, over all azimuth angles (see solid lines top row, [Figure 11](#fig-lca-ht-ws)). The increase in from (i.e., ), with increasing trajectory angle is shown on the bottom row of [Figure 11](#fig-lca-ht-ws) and exhibits a similar relationship 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.

At the stand scale, increasing the hydrometeor trajectory angle results in a substantial rise in the VoxRS measured over relatively common estimated wind speeds. For example, with a wind speed of 1 m s-1 and estimated trajectory angle of 48°, the increased by a fraction of 0.14 and 0.12 for the PWL and FT forest plots respectively in [Figure 11](#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. A similar rate of increase in was observed between both the FT and PWL forest plots up to around 60° or 1.5 m s-1. 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 .

|  |
| --- |
| Figure 11: Plots showing the relationship between hydrometeor trajectory angle (left) and wind speed (right) with mean plot-wide snow-leaf contact area, (top row) and the increase in mean plot-wide , 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 3](#eq-ta) and an observed event hydrometeor velocity of 0.9 m s-1. The solid lines (VoxRS) represent the mean (top) or increase in mean (bottom) for a single zenith angle observed from VoxRS across all grid cells for each forest plot and across all azimuth angles. The shaded area represents 1 standard deviation above and below the observed VoxRS mean. The dashed lines (Fitted) represent predictions from [Equation 9](#eq-lca-ac) (top) and [Equation 10](#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 VoxRS measurements at FT and PWL for simulated hydrometeor trajectory angles (see dashed lines in bottom row of [Figure 11](#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.

The resulting coefficients for , and after the nls fit to the VoxRS dataset 0.381, 46.864 and 25.8 respectively for PWL. For FT the resulting coefficents for , and from nls were 0.381, 46.864 and 25.8 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 9](#eq-lca-ac) is shown in the dashed lines in the top row of [Figure 11](#fig-lca-ht-ws) and follows closely to the VoxRS measured mean . Model error statistics shown in [Table 4](#tbl-lca-mod-err) demonstrate that [Equation 9](#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 4](#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.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 4: Model error statistics calculated for the prediction of leaf contact area from trajectory angle using [Equation 10](#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 8](#eq-lca-ip) in estimating throughfall () was assessed at the plot scale for both FT and PWL. Hydrometeor terminal velocity measured at PWL station, wind speed 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 from UAV-lidar averaged over each forest plot, an value of 1 was chosen based on the close alignment of interception efficiency and to the 1:1 line in [Figure 9](#fig-lca-vs-ip), height of wind within the canopy of 1.3 m, and the constants listed below [Equation 10](#eq-lca-inc).

Predicted values of observed and modelled interception efficiency and are shown in [Table 5](#tbl-vb-plot-err) along with corresponding error statistics. [Figure 12](#fig-event-tf) shows both the vector-based (VB) method, computed using [Equation 8](#eq-lca-ip) with adjusted for estimated hydrometeor trajectory angle, closely matches UAV-lidar measurements of throughfall with estimates of kg m-2 and kg m-2, compared to observed of kg m-2 and kg m-2 for the PWL and FT plots respectively. [Table 5](#tbl-vb-plot-err) shows the VB model has a very low absolute percent error compared to the Nadir model for PWL however for FT there is only slight improvement. However, for both forest plots VB modelled throughfall is less than the UAV-lidar observations resulting in a positive bias. This positive bias was expected as the UAV-lidar measurements of throughfall are inherently underestimates since they include some amount of unloading and redistribution. Therefore, if measurements of throughfall without unloading and redistribution could have been collected it is expected the VB-model would have further reduced error compared to the Nadir model for both FT and PWL. The overall improved performance of the VB model at PWL compared to FT, shown in [Table 5](#tbl-vb-plot-err) may be attributed to more of the PWL forest plot being influenced by the shifted hydrometeor trajectory due to the relatively smaller gaps in the canopy compared to the FT plot.

|  |
| --- |
| Figure 12: 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 8](#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 8](#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. |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 5: 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. Units for ip and tf are (-) and (kg m⁻²) respectively. The ‘mod\_type’ column refers to the method used to estimate ip and tf. The vector-based (VB) method utilized [Equation 8](#eq-lca-ip) with adjusted for trajectory angle. The nadir method also utilized [Equation 8](#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. The Mean Bias was calculated as observed minus modelled and Perc. Error is the percent error between predicted and observed values.   | plot | val\_name | mod\_type | obs\_val | mod\_val | Mean Bias | Perc. Error | | --- | --- | --- | --- | --- | --- | --- | | FT | ip | VB-model | 0.22 | 0.24 | -0.02 | -7.77 | | FT | ip | Nadir-model | 0.22 | 0.20 | 0.02 | 9.58 | | FT | tf | VB-model | 22.30 | 21.81 | 0.49 | 2.22 | | FT | tf | Nadir-model | 22.30 | 22.91 | -0.61 | -2.73 | | PWL | ip | VB-model | 0.41 | 0.42 | 0.00 | -0.85 | | PWL | ip | Nadir-model | 0.41 | 0.37 | 0.05 | 11.72 | | PWL | tf | VB-model | 16.81 | 16.71 | 0.10 | 0.60 | | PWL | tf | Nadir-model | 16.81 | 18.20 | -1.39 | -8.26 | |

# 5. Discussion

The point scale observations presented in this study showed no relationship between air temperature and interception efficiency [Figure 5](#fig-lai-met-ip) which differs from existing studies which suggested either a positive (Storck et al., 2002) or negative (Hedstrom & Pomeroy, 1998). An increase in interception efficiency before unloading was observed with increasing wind speed at two SCLs, which were sheltered to the predominant wind direction, and is attributed to an associated increase in [Figure 5](#fig-lai-met-ip). These results are consistent with Schmidt & Troendle (1989) who observed a slight increase in interception with increasing wind speeds up to 6 m s-1, and speculated this may be due to a greater “snowfall shadow” created by the forest for higher wind speeds. Compared to the influence of wind speed, interception efficiency showed smaller sensitivity to canopy snow load. The slight increase in interception efficiency for smaller canopy snow loads and decline in interception efficiency for larger canopy snow loads is attributed to the influence of canopy snow load on . While this effect was observed to be small in [Figure 5](#fig-lai-met-ip), it is like 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 also found declining interception efficiency at high snow loads. The observations presented in [Figure 5](#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 (Cebulski & Pomeroy (2024)) and did not show evidence of reaching a maximum canopy snow load. The canopy snow load increased linearly with snowfalls up to 45 kg m-2 [Figure 3](#fig-scl-w-sf) with no evidence of approaching a maximum canopy snow load. The strong exponential decline in interception efficiency observed with increasing event snowfall in Satterlund & Haupt (1967), Hedstrom & Pomeroy (1998), Storck et al. (2002) and Moeser et al. (2015) may be a result of increased unloading rates as branches bend under heavy snow loads and hence mix ablation and interception processes to varying degrees. The longer duration between site visits in (Hedstrom & Pomeroy, 1998; Moeser et al., 2015; Satterlund & Haupt, 1967; Schmidt & Gluns, 1991) increase the likelihood of canopy snow ablation in their throughfall measurements compared to the higher temporal resolution measurements in this study. Lundquist et al. (2021) reported improved simulation of subcanopy snow accumulation without the use of a maximum canopy snow load 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. Models are available to predict the accretion of ice on tree canopies (e.g., Nock et al., 2016) however, 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 suggested by Hedstrom & Pomeroy (1998) has not been provided in the literature. Measurements of interception efficiency and canopy structure collected in this study corroborated with the Hedstrom & Pomeroy (1998) theory and showed a large fraction of snow intercepted on the lee side of individual trees as shown in [Figure 7](#fig-lidar-tf-ip) due to predominately non-vertical hydrometeor trajectory angles which increased . It was found that the hydrometeor trajectory angle over the March 13-14th snowfall event observed in [Figure 8](#fig-hemi-ip-cc) could be predicted by using the observed hydrometeor fall velocity and a horizontal wind speed selected at one-third of the mean canopy height above the ground. A wind speed of one-third the mean canopy height is thought to be important for canopy snow accumulation as a large fraction of the horizontal cross sectional area of the needleleaf canopy in this study site is at this height. While a wind speed selected at a height higher within the canopy may have a higher speed and thus more horizontal trajectory angle, less canopy elements at this height would be available for contacting incoming hydrometeors. This is interpreted to be why the trajectory angle was overestimated when using the average wind speed integrated over the height of the canopy. Katsushima et al. (2023), also proposed the wind speed at one-third the canopy height for for modelling unloading of canopy snow as it corresponds to the centre of gravity when the horizontal projection of the canopy is assumed to be a triangle. However, there is uncertainty in the transferability of one-third canopy height observed here to other environments due to differing tree structures, and species such as those with a larger trunk space or have more of their canopy contact area at higher heights above the ground (i.e., some deciduous canopies). Moreover, [Equation 3](#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 3](#eq-ta) could utilize wind speed selected at one-third if the forest species and size is similar to those investigated in this study, while different species and canopy structures will require future research.

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 many existing snow interception parameterizations (Hedstrom & Pomeroy, 1998; Moeser et al., 2015; Satterlund & Haupt, 1967; Storck et al., 2002). To address this a new snow interception parameterization, [Equation 8](#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 and is consistent with the rainfall interception literature (Valante et al., 1997). [Equation 8](#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 8](#eq-lca-ip) is that the association between and interception efficiency, as shown in [Figure 9](#fig-lca-vs-ip), does not follow a 1:1 line as falling snow hydrometeors may bounce off the canopy elements. Some unloading and redistribution of snow during and between UAV-lidar scans may have increased observed throughfall depths and therefore generated some bias in the model fit to these observations. Efforts made to estimate unloading over the snowfall event provided a good match with the vector-based model. The new snow interception routine is also similar to many recent rainfall interception studies, which calculate throughfall as a function of (e.g., Valante et al., 1997). However, in Valante et al. (1997), rainfall interception is assumed to be completely efficient (i.e., = 1) and 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 1](#fig-ws-vs-ta), this still may 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 in snow-dominated basins.

Estimates of , are required in order to use [Equation 10](#eq-lca-inc), which depends on wind speed and hydrometeor velocity as shown in [Equation 3](#eq-ta). [Figure 1](#fig-ws-vs-ta) shows exhibits relatively little sensitivity depending on hydrometeor terminal fall velocity compared to the significant change in with height height above the snowpack as shown in [Figure 10](#fig-wind-profiles). Thus choosing an appropriate height of wind speed has important implications in correctly determining the trajectory angle during snowfall and also determining interception efficiency. Determining the hydrometeor velocity is another potential source of uncertainty when using the [Equation 3](#eq-ta) equation, however due to the low sensitivity and relatively low range in physically possible values (e.g., Thériault et al., 2021) and could be approximated by common values in the literature. While wind speed and direction were shown to be important factors influencing the portion of the hemisphere that governed snow accumulation in this study [Figure 8](#fig-hemi-ip-cc) directional and spatial differences across small length scales (0.25m) limited the application of [Equation 8](#eq-lca-ip) and [Equation 9](#eq-lca-ac) to the plot-scale. Significant scatter in VoxRS measured at the 0.25 m grid resolution, illustrated by the high standard deviation in [Figure 11](#fig-lca-ht-ws), resulted from directional (azimuth) and spatial differences in canopy structure. This large scatter suggests the observed relationships in [Figure 11](#fig-lca-ht-ws) are only applicable at the forest stand scale where the sub metre variability begin to average out. At this scale, [Equation 10](#eq-lca-inc), which uses trajectory angle alone, could be sufficient to determine and thus .

A substantial increase in plot scale was shown as a result of increasing hydrometeor trajectory angle [Figure 11](#fig-lca-ht-ws) 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 5](#fig-lai-met-ip) was relatively small. The negligible change in VoxRS measured after a large snowfall event and absence of a strong relationship at the point scale in [Figure 4](#fig-scl-ip-avg-event) and [Figure 5](#fig-lai-met-ip) suggests incorporating canopy snow load in interception efficiency parameterizations may not always be necessary. This is interpreted to be due to compensatory effects, where snow load may increase the for vertical zenith angles as the intercepted snow snow bridges gaps in the canopy elements. However, branch bending may also lead to a decrease in 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 presented here. An existing method proposed in Hedstrom & Pomeroy (1998) to scale canopy coverage with wind speed failed to reproduce the observations presented in [Figure 11](#fig-lca-ht-ws). A new method is proposed which uses logistic function to calculate as a function of and . Further work is required to refine the relationship proposed in [Equation 10](#eq-lca-inc) across a range of tree species and densities, determine how to calculate the maximum canopy snow load, reassess canopy snow ablation parameterizations of the new snow interception routine. The methodology applied in this study may also be applicable to other research concerned with the transmittance of solar radiation through the canopy and how this differes over zenith angles during different times of day and season and forest structures and tree species.

Although the performance improvement in the VB model compared to the Nadir model is relatively small, especially for FT, the positive bias of the VB model is preferred due to uncertainties with the throughfall measurements. An overestimate of interception efficiency was expected as the observations of interception efficiency are inherently underestimates due to some unloading and redistribution of snow over the March 13-14 snowfall event. Therefore the VB model, with slightly lower predicted throughfall, would better match observations that included less unloading and redistribution and thus would also have lower observed throughfall compared to the observations presented in [Table 5](#tbl-vb-plot-err). Conversely, the Nadir model which has a stronger negative bias, would result in further overestimates of throughfall if measurements of throughfall without unloading could have been collected. Although the Nadir model provided good performance for this event, a snowfall event with stronger wind speeds may increase in further resulting in worse model performance of the Nadir model. Conversely, areas with close to 1, which would not be as senstivive to [Equation 9](#eq-lca-ac), or during low wind speeds the Nadir model would have similar performance to the vector-based model. While the VB model acts to increase interception efficiency with wind speed, several studies suggest that canopy snow ablation increases as a result of wind induced unloading (Bartlett & Verseghy, 2015; Betts & Ball, 1997; Lumbrazo et al., 2022; Roesch et al., 2001; Wheeler, 1987). While these studies have been used to develop parameterizations for wind induced unloading, they were not based on direct measurements of canopy snow unloading and further research is required to better refine these relationships to understand how wind influences unloading of canopy snow after it is intercepted. Once the VB model is combined with a wind-induced canopy snow unloading parameterization, the overall influence of wind on canopy snow interception will be balanced to some extent.

# 6. Conclusions

* New observations of snow interception collected at both high temporal and spatial resolutions provided insights on the applicability of existing theories to this research site.
* A maximum canopy snow load was not approached or observed for snowfalls up to 45 kg m-2.
* Basically at the point scale interception efficiency can be assumed to be constant event over a wide range in meterological conditions. No association of air temperature with interception efficiency was observed from the high-frequency point scale measurements. 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 interception efficiency at a particular site. 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 compared to calm conditions with vertical hydrometeor trajectories in the discontinuous subalpine forest in this study. The effect of wind on leaf contact area can have large implications for interception efficiency. 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.
* 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 ablation processes. Future work will involve revising canopy snow ablation routines that are consistent with this new snow interception routine.

# 7. Acknowledgments

We wish to acknowledge financial support from the University of Saskatchewan Dean’s Scholarship, Natural Sciences and Engineering Research Council of Canada, Global Water Futures Programme, Alberta Innovates and the Canada Research Chairs Programme. We thank Madison Harasyn, Hannah Koslowsky, Kieran Lehan, Lindsey Langs and Fortress Mountain Resort for their help in the field. Madison Harasyn, Alistair Wallace, and Rob White contributed to developing the UAV-lidar processing workflow.

# 8. Data Availability

The authors declare there are no competing interests.

# 9. References

Axelsson, P. (2000). DEM Generation from laser scanner data using adaptive TIN models. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *33*, 110–117.

Bartlett, P. A., & Verseghy, D. L. (2015). Modified treatment of intercepted snow improves the simulated forest albedo in the Canadian Land Surface Scheme. *Hydrological Processes*, *29*(14), 3208–3226. <https://doi.org/10.1002/HYP.10431>

BayesMap Solutions. (2024). *BayesStripAlign*. <https://bayesmap.com/products/bayesstripalign/>

Betts, A. K., & Ball, J. H. (1997). Albedo over the boreal forest. *Journal of Geophysical Research: Atmospheres*, *102*(D24), 28901–28909. https://doi.org/<https://doi.org/10.1029/96JD03876>

Calder, I. R. (1990). *Evaporation in the uplands*. Wiley.

Cebulski, A., & Pomeroy, J. W. (2024). The theoretical underpinnings of snow interception and ablation parameterizations. *Wiley Interdisciplinary Reviews: Water*, *In Review*.

Chianucci, F., & Macek, M. (2023). hemispheR: an R package for fisheye canopy image analysis. *Agricultural and Forest Meteorology*. <https://doi.org/10.1016/j.agrformet.2023.109470>

Cionco, R. M. (1965). A Mathematical Model for Air Flow in a Vegetative Canopy. *Journal of Applied Meteorology (1962)*, *4*(4), 517–522. https://doi.org/<https://doi.org/10.1175/1520-0450(1965)004<0517:AMMFAF>2.0.CO;2>

Clark, M. P., Wood, A., Nijssen, B., Bennett, A., Knoben, W., & Lumbrazo, C. (2020). *SUMMA v3.0.3*. Zenodo. <https://doi.org/10.5281/zenodo.4558054>

Dai, Y., Yuan, H., Xin, Q., Wang, D., Shangguan, W., Zhang, S., Liu, S., & Wei, N. (2019). Different representations of canopy structure—A large source of uncertainty in global land surface modeling. *Agricultural and Forest Meteorology*, *269-270*(135), 119–135. <https://doi.org/10.1016/j.agrformet.2019.02.006>

Deems, J. S., Painter, T. H., & Finnegan, D. C. (2013). Lidar measurement of snow depth: A review. *Journal of Glaciology*, *59*(215), 467–479. <https://doi.org/10.3189/2013JoG12J154>

Ellis, C. R., Pomeroy, J. W., & Link, T. E. (2013). Modeling increases in snowmelt yield and desynchronization resulting from forest gap-thinning treatments in a northern mountain headwater basin. *Water Resources Research*, *49*(2), 936–949. <https://doi.org/10.1002/wrcr.20089>

Essery, R., Pomeroy, J. W., Parviainen, J., & Storck, P. (2003). Sublimation of snow from coniferous forests in a climate model. *Journal of Climate*, *16*(11), 1855–1864. <https://doi.org/10.1175/1520-0442(2003)016<1855:SOSFCF>2.0.CO;2>

Floyd, W. C. (2012). *Snowmelt energy flux recovery during rain-on-snow in regenerating forests* [PhD Thesis]. *August*, 180.

Floyd, W., & Weiler, M. (2008). Measuring snow accumulation and ablation dynamics during rain-on-snow events: innovative measurement techniques. *Hydrological Processes*, *22*(24), 4805–4812.

Fryer, G. I., & Johnson, E. A. (1988). Reconstructing Fire Behaviour and Effects in a Subalpine Forest. *The Journal of Applied Ecology*, *25*(3), 1063–1072.

Gelfan, A. N., Pomeroy, J. W., & Kuchment, L. S. (2004). Modeling forest cover influences on snow accumulation, sublimation, and melt. *Journal of Hydrometeorology*, *5*(5), 785–803. <https://doi.org/10.1175/1525-7541(2004)005<0785:MFCIOS>2.0.CO;2>

Golding, D. L., & Swanson, R. H. (1978). Snow accumulation and melt in small forest openings in Alberta. *Canadian Journal of Forest Research*, *8*(4), 380–388. https://doi.org/<https://doi.org/10.1139/x78-057>

Harder, P., & Pomeroy, J. W. (2013). Estimating precipitation phase using a psychrometric energy balance method. *Hydrological Processes*, *27*(13), 1901–1914. https://doi.org/<https://doi.org/10.1002/hyp.9799>

Harder, P., Pomeroy, J. W., & Helgason, W. D. (2020). Improving sub-canopy snow depth mapping with unmanned aerial vehicles: Lidar versus structure-from-motion techniques. *Cryosphere*, *14*(6), 1919–1935. <https://doi.org/10.5194/tc-14-1919-2020>

Harpold, A. A., Krogh, S. A., Kohler, M., Eckberg, D., Greenberg, J., Sterle, G., & Broxton, P. D. (2020). Increasing the efficacy of forest thinning for snow using high-resolution modeling: A proof of concept in the Lake Tahoe Basin, California, USA. *Ecohydrology*, *13*(4). <https://doi.org/10.1002/eco.2203>

Hedstrom, N. R., & Pomeroy, J. W. (1998). Measurements and modelling of snow interception in the boreal forest. *Hydrological Processes*, *12*(10-11), 1611–1625. <https://doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11<1611::AID-HYP684>3.0.CO;2-4>

Herwitz, S. R., & Slye, R. E. (1995). Three-dimensional modeling of canopy tree interception of wind-driven rainfall. *Journal of Hydrology*, *168*(1-4), 205–226. <https://doi.org/10.1016/0022-1694(94)02643-P>

Hijmans, R. J. (2024). *terra: Spatial Data Analysis*. <https://cran.r-project.org/package=terra>

Katsushima, T., Kato, A., Aiura, H., Nanko, K., Suzuki, S., Takeuchi, Y., & Murakami, S. (2023). Modelling of snow interception on a Japanese cedar canopy based on weighing tree experiment in a warm winter region. *Hydrological Processes*, *37*(6), 1–16. <https://doi.org/10.1002/hyp.14922>

Kim, E., Gatebe, C., Hall, D., Newlin, J., Misakonis, A., Elder, K., Marshall, H. P., Hiemstra, C., Brucker, L., De Marco, E., Crawford, C., Kang, D. H., & Entin, J. (2017). NASA’s snowex campaign: Observing seasonal snow in a forested environment. *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 1388–1390. <https://doi.org/10.1109/IGARSS.2017.8127222>

Kozak, A., & Kozak, R. A. (1995). Notes on regression through the origin. *Forestry Chronicle*, *71*(3), 326–330.

Langs, L. E., Petrone, R. M., & Pomeroy, J. W. (2020). A 18O and 2H stable water isotope analysis of subalpine forest water sources under seasonal and hydrological stress in the Canadian Rocky Mountains. *Hydrological Processes*, *34*(26), 5642–5658. <https://doi.org/10.1002/hyp.13986>

LAStools. (2024). *Efficient LiDAR Processing Software (version 240220, academic)*. <http://rapidlasso.com/LAStools>

Lehtonen, I., Hoppula, P., Pirinen, P., & Gregow, H. (2014). Modelling crown snow loads in Finland: a comparison of two methods. *Silva Fennica (Helsinki, Finland : 1967)*, *48*(3).

Lehtonen, I., Kämäraïnen, M., Gregow, H., Venälaïnen, A., & Peltola, H. (2016). Heavy snow loads in Finnish forests respond regionally asymmetrically to projected climate change. *Natural Hazards and Earth System Sciences*, *16*(10), 2259–2271. <https://doi.org/10.5194/nhess-16-2259-2016>

Lumbrazo, C., Bennett, A., Currier, W. R., Nijssen, B., & Lundquist, J. (2022). Evaluating Multiple Canopy-Snow Unloading Parameterizations in SUMMA With Time-Lapse Photography Characterized by Citizen Scientists. *Water Resources Research*, *58*(6), 1–22. <https://doi.org/10.1029/2021WR030852>

Lundberg, A. (1993). Evaporation of intercepted snow — Review of existing and new measurement methods. *Journal of Hydrology*, *151*(2), 267–290. https://doi.org/<https://doi.org/10.1016/0022-1694(93)90239-6>

Lundberg, A., & Hallidin, S. (1994). Evaporation of intercepted snow: Analysis of governing factors. *Water Resources Research*, *30*(9), 2587–2598. <https://doi.org/10.1029/94WR00873>

Lundquist, J. D., Dickerson-Lange, S., Gutmann, E., Jonas, T., Lumbrazo, C., & Reynolds, D. (2021). Snow interception modelling: Isolated observations have led to many land surface models lacking appropriate temperature sensitivities. *Hydrological Processes*, *35*(7), 1–20. <https://doi.org/10.1002/hyp.14274>

Mahat, V., & Tarboton, D. G. (2014). Representation of canopy snow interception, unloading and melt in a parsimonious snowmelt model. *Hydrological Processes*, *28*(26), 6320–6336. <https://doi.org/10.1002/hyp.10116>

Moeser, D., Stähli, M., & Jonas, T. (2015). Improved snow interception modeling using canopy parameters derived from airborne LiDAR data. *Water Resources Research*, *51*(7), 5041–5059. https://doi.org/<https://doi.org/10.1002/2014WR016724>

Musselman, K. N., Pomeroy, J. W., & Link, T. E. (2015). Variability in shortwave irradiance caused by forest gaps: Measurements, modelling, and implications for snow energetics. *Agricultural and Forest Meteorology*, *207*, 69–82. https://doi.org/<https://doi.org/10.1016/j.agrformet.2015.03.014>

Natural Resources Canada. (2024). *Precise point positioning*. <https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/tools-outils/ppp.php>

Niu, G. Y., & Yang, Z. L. (2004). Effects of vegetation canopy processes on snow surface energy and mass balances. *Journal of Geophysical Research D: Atmospheres*, *109*(23), 1–15. <https://doi.org/10.1029/2004JD004884>

Nock, C. A., Lecigne, B., Taugourdeau, O., Greene, D. F., Dauzat, J., Delagrange, S., & Messier, C. (2016). Linking ice accretion and crown structure: towards a model of the effect of freezing rain on tree canopies. *Annals of Botany*, *117*(7), 1163–1173.

Pomeroy, J. W., Fang, X., & Ellis, C. R. (2012). Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. *Hydrological Processes*, *26*(12), 1891–1904. <https://doi.org/10.1002/hyp.9248>

Pomeroy, J. W., & Gray, D. M. (1995). *Snowcover Accumulation, Relocation and Management* (NHRI Scien, p. 144). National Hydrology Research Institute, Environment Canada, Saskatoon, Canada.

Pomeroy, J. W., Marsh, P., & Gray, D. M. (1997). Application of a distributed blowing snow model to the arctic. *Hydrological Processes*, *11*(11), 1451–1464. <https://doi.org/10.1002/(sici)1099-1085(199709)11:11<1451::aid-hyp449>3.0.co;2-q>

Pomeroy, J. W., Parviainen, J., Hedstrom, N., & Gray, D. M. (1998). Coupled modelling of forest snow interception and sublimation. *Hydrological Processes*, *12*(15), 2317–2337. <https://doi.org/10.1002/(SICI)1099-1085(199812)12:15<2317::AID-HYP799>3.0.CO;2-X>

R Core Team. (2022). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. <https://www.r-project.org/>

R Core Team. (2024). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. <https://www.r-project.org/>

Rittger, K., Raleigh, M. S., Dozier, J., Hill, A. F., Lutz, J. A., & Painter, T. H. (2020). Canopy Adjustment and Improved Cloud Detection for Remotely Sensed Snow Cover Mapping. *Water Resources Research*, *56*(6), n/a. <https://doi.org/10.1029/2019WR024914>

Roesch, A., Wild, M., Gilgen, H., & Ohmura, A. (2001). A new snow cover fraction parameterization for the ECHAM4 GCM. *Climate Dynamics*, *17*(12), 933–946. <https://doi.org/10.1007/s003820100153>

Safa, H., Krogh, S. A., Greenberg, J., Kostadinov, T. S., & Harpold, A. A. (2021). Unraveling the Controls on Snow Disappearance in Montane Conifer Forests Using Multi-Site Lidar. *Water Resources Research*, *57*(12), 1–20. <https://doi.org/10.1029/2020WR027522>

Satterlund, D. R., & Haupt, H. F. (1967). Snow catch by Conifer Crowns. *Water Resources Research*, *3*(4), 1035–1039. https://doi.org/<https://doi.org/10.1029/WR003i004p01035>

Schmidt, R. A., & Gluns, D. R. (1991). Snowfall interception on branches of three conifer species. *Canadian Journal of Forest Research*, *21*(8), 1262–1269. https://doi.org/<https://doi.org/10.1139/x91-176>

Schmidt, R. A., & Pomeroy, J. W. (1990). Bending of a conifer branch at subfreezing temperatures: implications for snow interception. *Canadian Journal of Forest Research*, *20*(8), 1251–1253. <https://doi.org/10.1139/x90-165>

Schmidt, R. A., & Troendle, C. A. (1989). Snowfall into a forest and clearing. *Journal of Hydrology*, *110*(3-4), 335–348. <https://doi.org/10.1016/0022-1694(89)90196-0>

Smith, C. D. (2007). Correcting the wind bias in snowfall measurements made with a Geonor T-200B precipitation gauge and alter wind shield. *87th AMS Annual Meeting*.

Staines, J., & Pomeroy, J. W. (2023). Influence of forest canopy structure and wind flow on patterns of sub-canopy snow accumulation in montane needleleaf forests. *Hydrological Processes*, *37*(10), 1–19. <https://doi.org/10.1002/hyp.15005>

Storck, P., Lettenmaier, D. P., & Bolton, S. M. (2002). Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. *Water Resources Research*, *38*(11), 1–16. <https://doi.org/10.1029/2002wr001281>

Thériault, J. M., Déry, S. J., Pomeroy, J. W., Smith, H. M., Almonte, J., Bertoncini, A., Crawford, R. W., Desroches-Lapointe, A., Lachapelle, M., Mariani, Z., Mitchell, S., Morris, J. E., Hébert-Pinard, C., Rodriguez, P., & Thompson, H. D. (2021). Meteorological observations collected during the Storms and Precipitation across the continental Divide Experiment (SPADE), April-June 2019. *Earth System Science Data*, *13*(3), 1233–1249. <https://doi.org/10.5194/essd-13-1233-2021>

Troendle, C. A. (1983). The Potential for Water Yield Augmentation From Forest Management in the Rocky Mountain Region. *Journal of the American Water Resources Association*, *19*(3), 359–373. <https://doi.org/10.1111/j.1752-1688.1983.tb04593.x>

Valante, F., David, J. S., & Gash, J. H. C. (1997). Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. *Journal of Hydrology*, *190*(1-2), 141–162. <https://doi.org/10.1016/S0022-1694(96)03066-1>

Van Stan, J. T., Siegert, C. M., Levia, D. F., & Scheick, C. E. (2011). Effects of wind-driven rainfall on stemflow generation between codominant tree species with differing crown characteristics. *Agricultural and Forest Meteorology*, *151*(9), 1277–1286. <https://doi.org/10.1016/j.agrformet.2011.05.008>

Varhola, A., Coops, N. C., Weiler, M., & Moore, R. D. (2010). Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*, *392*(3-4), 219–233. <https://doi.org/10.1016/j.jhydrol.2010.08.009>

Verseghy, D. L. (2017). *Class – The Canadian Land Surface Scheme (version 3.6.1) technical documentation.* (January; p. 174). Environment; Climate Change Canada Internal Rep. <https://zenodo.org/record/6562376/files/Verseghy_2017_CLASSv3.6.1_Documentaton.pdf>

Vionnet, V., Mortimer, C., Brady, M., Arnal, L., & Brown, R. (2021). Canadian historical Snow Water Equivalent dataset (CanSWE, 1928–2020). *Earth System Science Data*, *13*(9), 4603–4619.

Wheater, H. S., Pomeroy, J. W., Pietroniro, A., Davison, B., Elshamy, M., Yassin, F., Rokaya, P., Fayad, A., Tesemma, Z., Princz, D., Loukili, Y., DeBeer, C. M., Ireson, A. M., Razavi, S., Lindenschmidt, K., Elshorbagy, A., MacDonald, M., Abdelhamed, M., Haghnegahdar, A., & Bahrami, A. (2022). Advances in modelling large river basins in cold regions with Modélisation Environmentale Communautaire—Surface and Hydrology (MESH), the Canadian hydrological land surface scheme. *Hydrological Processes*, *36*(4), 1–24.

Wheeler, K. (1987). *Interception and redistribution of snow in a subalpine forest on a storm-by-storm basis*. Western Snow Conference. <http://sites/westernsnowconference.org/PDFs/1987Wheeler.pdf>