The influence of ground and LiDAR-derived forest structure metrics on snow accumulation and ablation in disturbed forests

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Abstract. The severity and extent of the current mountain pine beetle (MPB) infestation in British Columbia’s lodgepole pine forests has raised concerns about potential impacts on water resources. Forest structure changes resulting from defoliation, limb loss, windthrow and salvage harvesting in infested stands may increase snow accumulation and melting rates below the forest canopy due to reduced interception and potentially higher levels of radiation reaching the forest floor. This change in radiation regime can alter runoff regimes, increasing the risk and magnitude of spring flooding and decreasing summer streamflow. In order to quantify these effects, we must improve our understanding of the link between forest structure and snow processes. In this research we investigated the correlation between LiDAR-derived canopy metrics and indicators of snow accumulation and ablation across a range of sites in the interior of British Columbia. A LiDAR-derived forest cover parameter was the most significant predictor of peak snow accumulation ($r^2 = 0.70, p < 0.001$) and maximum snow ablation rate ($r^2 = 0.59, p < 0.01$). Improving our ability to quantify changes in forest structure at large scales will assist in developing more robust models of watershed processes.

Keywords. Snow accumulation, snow melt, ablation, LiDAR, mountain pine beetle, defoliation, forest structure, canopy metrics, forest cover.
1. Introduction

The role of vegetation cover in forest hydrology is well known, with forest stands playing a key role in a number of processes that ultimately impact stream discharge (Connaughton, 1935; Haupt, 1951; Robinson, 1998; Eisenbies et al., 2007; van Dijk & Keenan, 2007). These processes include the sublimation of snowfall intercepted by the canopies and returned to the atmosphere without falling to the ground, and evapo-transpiration in which water is either transpired or evaporated from the canopy itself (Brooks et al., 2003). In cold, dry environments, sublimation is a dominant process (Pomeroy et al., 2002; Buttle et al., 2005; Brook et al., 2003; Essery et al., 2003), with studies indicating that up to 60% of annual snowfall can be intercepted in dense coniferous forest canopies, of which 60 - 80% may be sublimated under certain conditions (Hedstrom & Pomeroy, 1998; Pomeroy et al., 1998). As a result, the removal or disturbance of forest cover in a watershed will lead to decreases in both interception and transpiration (Unnila et al., 2006), consequently resulting in an increase in discharge.

Forest cover also affects local microclimates, modifying temperature and radiation with subsequent impacts on overall water dynamics, especially in snow dominated regions (Essery, 2008). Reductions in forest cover increase incoming shortwave radiation reaching the forest floor, leading to greater temperatures and melt rates relative to denser stands (Essery, 2008; Boon, 2009). Paired plot studies have also demonstrated increases in snow accumulation with decreasing forest cover (e.g., Connaughton, 1935; Meagher, 1938; Haupt, 1951; Swanson & Stevenson, 1971; D’Eon, 2004; Winkler et al., 2005). Snow melting is also influenced by forest characteristics as canopies change the energy balance conditions in the ground by intercepting incoming shortwave radiation, which leads to lower temperatures and slower melting rates in a forest when compared to an open area (Essery, 2008). Additionally, forest cover shelters snow in the ground and reduces the eroding and sublimating effect of wind (Gary, 1975). These processes are of major importance in snow-dominated watersheds because if the time between peak snow accumulation and snow disappearance is relatively short, snowmelt discharges are potential sources of severe flooding (Brook et al.,
Flat catchments with little topographic variation, where all the snow melts simultaneously, are more susceptible to increasing snow melt rates and consequent flooding (Alila et al., 2007).

Lodgepole pine (*Pinus contorta*) forests of British Columbia, Canada, have been significantly impacted by a widespread infestation of mountain pine beetle (MPB) (*Dendroctonus ponderosae*). The current outbreak is the largest recorded in North America (Maclauchlan, 2007; Kurz, 2008), involving more than 135,000 km² of forest (BC Ministry of Forests, 2008). Following initial beetle attack, individual trees undergo gradual defoliation (3 – 5 years), branch loss (10 -15 years) and blow down (5 – 15 years) (Mitchell & Preisler, 1998). During the green-attack phase, trees show signs of MPB on the bark but retain green or yellowish foliage. This is followed by the red attack stage, where the needles turn reddish brown in the canopy. The final stage, grey attack, occurs once the needles fall to the ground. The outbreak in BC added structural complexity to an already heterogeneous landscape by initially affecting mature stands, followed by medium-aged forests. This infestation pattern resulted in a mosaic including mature grey-attack stands, medium-aged red-attack stands, unattacked pine stands due to small DBH, and salvage logging clearcuts. Previous studies show that large-scale impacts on forest hydrology can be expected from insect infestation. Following a MPB outbreak in Jack Creek (Montana, late 1970s), 35% pine mortality resulted in a statistically significant 15% increase in annual water yield in the watershed, as well as a 10% increase in low flows and early snow melt. Examples from Colorado, Montana and Wyoming provide similar indications that insect infestation can increase annual water yield by 11 - 28%, increase monthly low flows by 10 - 32%, increase monthly high flows by 14 - 52%, and potentially increase instantaneous peak flows (Unnila et al. 2006). With this evidence, the potential impacts of the current MPB outbreak in BC will likely include changes in interception, evaporation, transpiration, snowpack redistribution, melting, and groundwater storage, stream stability, water quality, hillslope processes, riparian functions and fisheries. Some local studies have already shown some of these impacts (Teti, 2008; Boon 2009).
Whilst forest structure has been demonstrated to have a critical influence on hydrological processes, it is difficult to measure in the field, especially over large areas. Light Detection and Ranging (LiDAR) is an active airborne remote sensing laser technology capable of providing detailed, spatially explicit, three-dimensional information on vegetation structure (Lefsky et al., 2002; Lim et al., 2003; Reutebuch et al., 2005; Wulder et al., 2008). LiDAR offers an innovative alternative to traditional field surveys for accurately estimating forest structure variables over the landscape. Because LiDAR systems detect the returns of laser pulses with canopy structural elements, is it analogous to snow and precipitation interception processes and thus conceptually links well to snow hydrology.

The relationship between forest cover and hydrologic response at the landscape level is important for policy makers, especially regarding harvesting regulations (BC Ministry of Forests, 2001). One of the concepts used to estimate the cumulative disturbance in catchments is called Equivalent Clear-Cut Area (ECA). First published by the US Department of Agriculture in 1974, this procedure has been used to evaluate the potential effect of harvesting on peak flows due to changes in forest composition (King, 1989), and could also be useful to address the MPB infestation. However, there are some issues regarding the use of the ECA method. First, it has been criticized for not being well linked to hydrologic impact (Caver, 2001; Ager & Clifton, 2005). Second, it has been calibrated to work below certain area thresholds, making its application over larger areas more difficult. Third, there is a lack of standard procedures for ECA calculation and many local variations (Ager & Clifton, 2005). Finally, as discussed by Ager & Clifton (2005), the ECA guidelines are currently based on harvesting as the main source of impact (King, 1989; BC Ministry of Forests, 2001), while the changes in forest structure due to insect infestation are different in nature. As a result, new guidelines describing the methods to derive ECA under these conditions are now needed by hydrologists and forest managers.

In this study we investigate the relationship between LiDAR-derived metrics of forest structure with indicators of snow interception and ablation across a range of forest plots with varying MPB infestation
levels. Analyzing these links at the plot level will provide useful data for further evaluation of the impacts of forest structure changes on snow hydrology at the watershed level, allowing the simulation of stream discharges. The results will also provide useful inputs for the creation of new methods to calculate defoliation-based ECA.

2. Methods

2.1 Study area and field inventory measurements

A total of 11 plots were established in the Quesnel and Vanderhoof Forest Districts in the interior of BC in order to represent a wide range of infestation conditions in lodgepole pine-dominated stands. Two of the plots were located in recent clearcuts to serve as reference sites for snow accumulation and ablation in the absence of forest cover (Table 1). Two plots were in stands under 15 years old (YR2, YR3) and one plot was in a 70 year old stand with a very high stem density (YR5). The two young stands and the overdense stand consisted of almost pure pine with DBH’s of 8 cm or less. As such, they had virtually no MPB attack due the beetle’s preference for larger trees (the 25% grey in YR5 was inferred to be due to competition and snow damage). Tree surveys were conducted during summer 2007 in each of two or four circular plots having a total area of 100, 200, 400 or 800 m² (depending on estimated stem density). Trees with DBH greater than 4 cm were counted and their species and defoliation condition were tabulated. Within each circular plot, DBH and height of a sub-sample of up to 20 trees (depending on the number of green and red pine trees) were measured. Calculated parameters included stems per hectare by species and condition (green, red, defoliated), mean diameter at breast height (DBH), basal area, mean and Lorey’s height. Basal area of defoliated trees was estimated using an alternate dataset which included DBH measurements for trees in different defoliation conditions. Since MPB attacked larger trees first, the average DBH difference between grey and green trees was extrapolated to the current dataset in order to obtain total basal area.

*Insert Table 1 here*
2.2 Snow surveys

Six snow surveys were conducted between late February and early May 2008 in 9 plots. Within each plot, 36 locations spaced 10 m apart in a grid were sampled (50 x 50 m plots). During each survey, snow depth was measured at each point with a fiberglass rod. Next to each plot, vertically integrated snow density was measured in a snow pit using a 10 cm diameter PVC pipe at the time of each snow survey. This density was multiplied by mean depth to obtain mean snow water equivalent (SWE) per plot per survey. Two additional plots were located in a dense grey stand (GY5) and a young 3 m regeneration stand (YR3). In these plots snow surveys were performed in a 50 x 50 m cross where SWE and snow density was measured with a standard snow tube in the center and four corners, while snow depths were measured in 5 m intervals within the cross. The average snow density was then used to estimate the SWE representative of the entire plot in each survey.

Two indicators of SWE accumulation were derived for each plot: absolute peak SWE (maximum SWE recorded among all surveys), and the SWE measured in early April. Snow ablation rates were calculated with the following equation:

\[
AR = \frac{(SWE_i - SWE_f)}{P}
\]  

[1]

Where \(AR\) is ablation rate (mm/day), \(SWE_i\) is the initial SWE (mm), \(SWE_f\) is the final SWE and \(P\) is the number of days between the measurement of \(SWE_i\) and \(SWE_f\). In this study, three ablation rate indicators were calculated by using absolute peak SWE, early April SWE and mid-April SWE as starting points (\(SWE_i\)). The last snow surveys in early May were used to obtain \(SWE_i\) in all cases. The ablation rate calculated between the last two consecutive surveys is considered the maximum ablation rate because during this period the temperatures are higher and the melting curves are steeper.

2.3 LiDAR acquisition and processing
LiDAR data was acquired in February 2008 by Terra Remote Sensing (Sidney, British Columbia, Canada) using the TRSI Mark II discrete return sensor mounted on a helicopter platform flying at a height of 800 m above ground level. The LiDAR sensor has a wavelength of 1,064 nm and was configured with a pulse repetition frequency of 50 kHz, maximum off-nadir scan angle of 15 degrees, and a fixed beam divergence angle of 0.5 mrad, resulting in an average footprint size of 0.35 m. Ground and non-ground returns were separated by the vendor using Terrascan v 4.006 (Terrasolid, Helsinki, Finland). Based on results reported by Bater & Coops (2009), a 1 m spatial resolution digital elevation model (DEM) was generated by applying a natural neighbour (Sibson, 1981; Sambridge et al., 1995) interpolation algorithm to the ground returns. The heights of the vegetation returns above the snow (ground was covered by an average of 50 cm at the time) were computed by subtracting the DEM heights from the vegetation return heights.

A number of plot-level variables were extracted from the LiDAR vegetation data based on previous research demonstrating their relationship with vertical structure and cover (e.g. Magnussen & Boudewin, 1998; Næsset, 2002; Lovell et al., 2003; Næsset, 2004; Anderson et al., 2005; Gobakken & Næsset, 2005; Hopkinson et al. 2006; Pesonen et al. 2008). These variables were used to characterize the distribution of LiDAR returns through the vertical vegetation profile in the same plot areas covered by the snow surveys (2,500 m²), and included: height percentiles (5 – 95%); mean, maximum, standard deviation, and coefficients of variation of vegetation return heights; and Weibull α and β parameters, where α provides a vertical scaling and positioning factor for movement of the distribution, and β provides the capacity to increase or decrease the breadth of the distribution (Bailey & Dell, 1973; Xu & Harrington, 1998). The natural logarithms of each variable were also computed. Finally, forest cover was also estimated at the plot level based on ratios between returns above 2 m and the total number of returns. Because changes in survey configuration such as an increase in lying altitude may affect the number and distribution of multiple returns (e.g. Morsdorf et al., 2008; Næsset, 2009), only first echoes were used to estimate cover.

2.4 Statistical analysis
The purpose of the statistical analysis was to determine which snow accumulation and ablation indicators showed the strongest correlations with forest structure metrics. Thus, absolute peak SWE, early April SWE and the three ablation indicators described above where correlated to a total of 27 ground and LiDAR-derived forest variables. A matrix of Pearson correlation coefficients (r) and significance levels (p) was used to determine the strength of these relationships.

3. Results

A standard forest inventory description of the plots is shown in Table 2, as well as the degree of MPB infestation expressed as the proportion of basal area affected by different attack levels (Figure 1). Results confirm that the plots have high variability in stand conditions, including three that contained mostly green trees and five older, larger stands with 66% to 90% of their stems defoliated (grey).

*Insert Table 2 here*

*Insert Figure 1 here*

The snow accumulation and ablation rate indicators shown in Table 3 indicate that the clearcuts were subject to greater peak SWE and ablation rates than the surrounding forested sites. Figure 2 shows the percentage of absolute peak SWE in all the forested sites relative to the nearby clearcuts, which varies between 93 and 72%. Maximum ablation rate was also lower in all the forested stands, ranging from 85 to 69% compared to nearby clearcuts. Changes in mean SWE estimated from the sequential snow surveys for some representative plots are shown in Figure 3. In Baker Creek as well as Vanderhoof, peak SWE was observed in different dates from early March to early April among the plots. In Baker Creek, only the clearcut’s peak occurred in mid-April, just before maximum ablation, while forested sites showed the highest snow accumulation earlier. In Vanderhoof, the clearcut and the dense stand (YR5) showed maximum peak in the early March survey, while it occurred in early April in the two grey stands.
Plot level LiDAR variables are summarized in Table 4. Absolute peak SWE and maximum ablation rate were most highly correlated with the LIDAR attributes (Table 5). Figure 4 shows the relationship of the two variables with the highest correlation with absolute peak SWE and maximum ablation rate. Forest cover was most highly correlated with both absolute peak SWE and maximum ablation rate, followed by 90% height percentile and height standard deviation, respectively.

4. Discussion

The results presented in this study show the high variability in stand physical characteristics, MPB infestation patterns and snow accumulation and ablation processes between plots. Forest structure variability is evident in the wide ranges of both ground and LiDAR-derived metrics between stands. Figures 2 and 3 indicate the clearcut plots accumulated more snow than the forested sites, which is consistent with other studies (e.g. Murray & Buttle, 2003; Winkler et al., 2005; Jost et al., 2007). Plot YR5 for example, located in an old (70 years) small DBH stand (10 m in mean height), had the densest forest cover and the smallest peak SWE and ablation rate, showing the strong effects of snow interception and the reduction of incoming shortwave radiation on the surface during the snow melting period.

All forest structure variables were negatively correlated with snow accumulation and ablation (Table 5), indicating that increases in forest cover are associated with reduced snow accumulation and ablation rates. The relationships between snow processes and LiDAR-derived forest cover are particularly strong. The
Capacity of LiDAR technology to characterize forest structure is evident as all LiDAR-derived variables showed significant correlations with absolute peak SWE, and only two did not produce similar results with maximum snow accumulation. In contrast, only three of the 18 ground-based variables describing forest structure and MPB infestation indicators were significant predictors of the dependent snow variables. LiDAR-derived forest cover, calculated as the ratio of the number of vegetation first returns to the total number of returns, is a function of the arrangement and density of canopy elements, which are in turn related to interception and ablation. Just as dense canopies intercept large amounts of snow, they also reflect a larger number of LiDAR pulses and shade the underlying ground surface from both solar and laser-emitted radiation. The fact that the forest structure variables that explained most of the variation in peak SWE were the same that were significantly correlated to maximum ablation rate suggests that these hydrological processes are driven by the same principles. Forest canopies intercept snow in a similar way as they intercept incoming shortwave radiation. These results go accordingly with several studies showing that changes in forest cover have a similar effect on both snow accumulation and melting (Anderson & Gleason, 1960; Hardy et al., 1990; McCaughey & Farnes, 2001; Hudson, 2000).

Linking the results presented in this study with new defoliation-based ECA guidelines will require further research. The strong correlations between LiDAR-derived forest cover and snow accumulation and ablation suggest that defoliation should be expressed in terms of forest cover in order to produce suitable guidelines. One of the current procedures used to estimate ECA is based on % of basal area removed by individual tree selection (BC Ministry of Forests, 2001). A similar approach could be undertaken to include defoliation-derived changes in forest cover and its correlation with snow processes to calculate ECA.

The main limitation of this research is the small sample size of 11 plots, which makes it difficult to extrapolate results to larger areas. However, the good correlations obtained between LiDAR variables and snow accumulation and ablation show promise for further research. It has been demonstrated here that
forest structure is strongly linked to snow processes, but additional work is required to directly link LiDAR-derived metrics to the timing and magnitude of seasonal stream discharge.

5. Conclusions
LiDAR technology has demonstrated utility in linking forest structure with snow accumulation and ablation. LiDAR-derived forest structure metrics were strong predictors of peak SWE and maximum ablation rates, showing significant correlations in most of the cases. Forest cover was the variable with the best performance for modelling changes in these hydrologic processes. This is consistent with the theory since forest cover is a good representation of the canopy attributes that explain interception. The similarity between peak SWE and maximum ablation rate regarding their correlations with forest structure variables lead us to conclude that the snow accumulation and melting patterns are both driven by the same canopy attributes, which are accurately characterized by LiDAR. Increasing forest cover reduces snow accumulation due to interception and sublimation, and it also reduces snow ablation rates by intercepting incoming radiation.

The results presented in this study can be used to infer changes in snow accumulation and melting following changes in forest cover. This is important for forest resource managers because they can predict potential responses of these snow processes to a wide range of practices such as thinning, harvesting, salvage logging or planting. The changes in cover associated with defoliation caused by the MPB in British Columbia can be incorporated in models to predict the hydrologic response of affected catchments at a broader scale. In order to achieve this, the next step is to link snow accumulation and ablation to streamwater discharge.

Acknowledgements
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References


Connaughton, C.A. 1935. The accumulation and rate of melting of snow as influenced by vegetation. J. For. 33(6): 564-569.


## Tables

### Table 1. Plot general information.

<table>
<thead>
<tr>
<th>Code</th>
<th>Original code</th>
<th>Reference clearcut</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (masl)</th>
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<td>BRC1</td>
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<td>-123.017</td>
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</tr>
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<td>VYN</td>
<td>CC1</td>
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<td>1,240</td>
</tr>
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<td>CC1</td>
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<td>900</td>
</tr>
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<td>CC1</td>
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</table>

1. YR = small DBH; RD = stand with predominant red attack; GY = stand with predominant grey attack; CC = clearcut.
2. From previous studies (Teti, 2008; Boon, 2009).

### Table 2. Ground-based plot information (from forest inventories performed during summer 2007).

<table>
<thead>
<tr>
<th>Plot</th>
<th>Trees (n/ha)</th>
<th>Mean DBH (cm)</th>
<th>Basal area (m²/ha)</th>
<th>Mean height (m)</th>
<th>Pine (%)</th>
<th>GN (%)</th>
<th>RD (%)</th>
<th>GY (%)</th>
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<tbody>
<tr>
<td>YR2</td>
<td>1,312</td>
<td>5.4</td>
<td>3.1</td>
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<td>69</td>
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<td>15</td>
<td>77</td>
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<td>1,800</td>
<td>18.5</td>
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<td>22</td>
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<td>78</td>
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* GN = healthy; RD = red attack; GY = grey attack. MPB distribution in % of total plot basal area including other species.

### Table 3. Snow survey results in spring 2008.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Peak SWE (mm)*</th>
<th>Mean Ablation rates (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absolute</td>
<td>Early April – early May</td>
</tr>
<tr>
<td>CC1</td>
<td>179 (36)</td>
<td>156 (25)</td>
</tr>
<tr>
<td>CC5</td>
<td>172 (17)</td>
<td>158 (16)</td>
</tr>
<tr>
<td>YR2</td>
<td>147 (37)</td>
<td>126 (59)</td>
</tr>
<tr>
<td>YR3</td>
<td>168 (47)</td>
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<td>150 (24)</td>
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<tr>
<td>GY10</td>
<td>149 (39)</td>
<td>149 (39)</td>
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</table>

* Standard deviation in parentheses.
Table 4. LiDAR-derived forest structure metrics.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Height standard deviation (m)</th>
<th>Forest cover &gt; 0.5 m (m)</th>
<th>Forest cover &gt; 2 m (m)</th>
<th>Height 60% percentile (m)</th>
<th>Height 90% percentile (m)</th>
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Table 5. List of forest structure variables with significant correlations with absolute peak SWE and maximum ablation rate.

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<tr>
<th>Source</th>
<th>Variable</th>
<th>Absolute peak SWE</th>
<th>Max. ablation rate</th>
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<td></td>
<td>r</td>
<td>r²</td>
<td>p</td>
<td>r</td>
<td>r²</td>
<td>p</td>
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<td>Ground inventories</td>
<td>Mean DBH</td>
<td>-0.781</td>
<td>0.609</td>
<td>0.005</td>
<td>-0.678</td>
<td>0.460</td>
<td>0.022</td>
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<tr>
<td></td>
<td>Mean height</td>
<td>-0.776</td>
<td>0.602</td>
<td>0.005</td>
<td>-0.678</td>
<td>0.460</td>
<td>0.022</td>
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<tr>
<td></td>
<td>Percentage of pine</td>
<td>-0.660</td>
<td>0.435</td>
<td>0.027</td>
<td>-0.621</td>
<td>0.385</td>
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<td>LiDAR</td>
<td>Mean height</td>
<td>-0.731</td>
<td>0.534</td>
<td>0.011</td>
<td>-0.631</td>
<td>0.398</td>
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<td>Height standard deviation</td>
<td>-0.712</td>
<td>0.519</td>
<td>0.012</td>
<td>-0.717</td>
<td>0.514</td>
<td>0.013</td>
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<td>Forest cover (&gt; 0.5 m)</td>
<td>-0.709</td>
<td>0.502</td>
<td>0.015</td>
<td>-0.737</td>
<td>0.543</td>
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<td>Forest cover (&gt; 2 m)</td>
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<td>Height 60% percentile</td>
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<td>0.544</td>
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<td>-0.653</td>
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<td>Height 90% percentile</td>
<td>-0.752</td>
<td>0.565</td>
<td>0.008</td>
<td>-0.683</td>
<td>0.466</td>
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</tbody>
</table>
Figures

Figure 1. Basal area per plot according to MPB infestation.

Figure 2. Absolute peak SWE and maximum ablation rate in forested plots relative to nearby clearcuts.

Figure 3. Snow water equivalent in Baker Creek (left) and Vanderhoof (right) plots.
Figure 4. Scatterplots of forest structure variables with the highest correlations with absolute peak SWE (top) and maximum ablation rate (bottom) (all correlations with p < 0.015).