Impact of Mountain Pine Beetle Infestation and Salvage Harvesting on Seasonal Snow Melt and Runoff

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Abstract

Forest disturbance has a significant impact on forest hydrology due to its effect on the forest canopy, which is important for precipitation interception, evapotranspiration, local meteorology, and snow accumulation and melt. This study examines the impact of mountain pine beetle infestation on forest canopy structure on the Nechako Plateau, and the resulting impacts on snow accumulation and ablation under varied climatic conditions. In high snow years, dead stands behave similarly to alive and clearcut stands due to the ability of large snowfalls to exceed the interception capacity of the canopy. In low to average snow years, however, distinct differences in snow accumulation in dead stands can be attributed to needle loss and canopy reduction due mainly to the loss of small branches and stems. Changing canopy conditions subsequently have a significant impact on local meteorological conditions. Snow ablation is thus driven largely by incoming shortwave radiation, which in dead stands is greater than in alive stands, but is not as great as in clearcuts. Additionally, longwave radiation emission in dead stands is much lower than in alive stands, substantially reducing its contribution to snowpack warming and ablation. Turbulent flux contributions to snow ablation are limited in forest stands, although they are increased slightly in dead stands over alive stands due to the more open structure. Stand-scale results were used to drive a physically-based, distributed hydrological model of the Van Tine Creek watershed and assess watershed-scale hydrologic response to four harvesting/infestation scenarios.

Keywords: snow accumulation, snow ablation, energy balance, runoff, forest canopy, interception, hydrologic modelling

Résumé

En raison de son effet sur la couverture forestière, qui est importante pour l'interception des précipitations, l'évatranspiration, la météorologie locale ainsi que l'accumulation et la fonte de la neige, la perturbation des forêts a des répercussions importantes sur leur hydrologie. L'étude examine les conséquences de l'infestation de dendroctone du pin ponderosa sur la structure de la couverture forestière du plateau de Nechako, et sur l'accumulation de neige et le taux d'ablation dans des conditions climatiques variées. Durant les années où les précipitations de neige sont importantes, les peuplements décimés se comportent plus ou moins de la même manière que les peuplements qui ont subi une coupe à blanc en raison de la capacité des fortes précipitations de neige à excéder la capacité d'interception de la couverture. Durant les années où les précipitations de neige sont faibles ou modérées, toutefois, les différences sensibles d'accumulation de neige dans les peuplements décimés peuvent être attribuées à la perte d'aiguilles et à la réduction de la couverture qui est principalement attribuable à la perte des petites branches et des tiges. Les changements dans l'état de la couverture entraînent des répercussions significatives sur les conditions météorologiques locales. L'ablation nivale est ainsi causée en bonne partie par la radiation à ondes courtes, laquelle est plus élevée dans les peuplements décimés que dans les peuplements vivants, mais inférieure à celle constatée dans les coupes à blanc. De plus, la radiation à grandes ondes dans les peuplements décimés est beaucoup plus faible que dans les peuplements vivants, ce qui réduit de manière importante sa contribution au réchauffement et à l'ablation de la neige accumulée. La contribution des flux de turbulence à l'ablation nivale est limitée dans les peuplements forestiers. On constate toutefois une légère augmentation dans les peuplements décimés par rapport aux peuplements vivants en raison de la structure plus ouverte. On a utilisé les résultats à l'échelle des peuplements pour concevoir un modèle hydrologique physique et distribué pour le bassin hydrologique de Van Tine Creek, et évaluer la réaction hydrologique à l'échelle du bassin aux quatre scénarios de récolte et d'infestation.

Mots-clés : accumulation de neige, ablation nivale, bilan énergétique, écoulement, couverture forestière, interception, modélisation hydrologique

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1 Introduction

1.1 Background

This research aims to determine how forest canopy change caused by mountain pine beetle (MPB) infestation affects snow accumulation and ablation at the stand and watershed scale. The current MPB epidemic in British Columbia (BC) began in 1999. As of 2008, over 50 million hectares of BC Crown forest have been damaged (>50% of merchantable pine), and the beetle infestation has spread to Alberta (BC Ministry of Forests and Range 2008). Given the magnitude of the area affected, the impacts will be wide-ranging, particularly since hydrology in much of this region is snowmelt-driven. Changes in snow accumulation and ablation due to beetle infestation will therefore have not only stand-scale effects, but will also impact watershed-scale, regional hydrology, with subsequent impacts on geomorphology, vegetation, and ecology.

Forest canopies play a significant role in snow-hydrology processes because of their role in interception and accumulation, and their impact on the energy balance. Forest canopies intercept snowfall, which can then sublimate or evaporate from the branches (Link and Marks 1999), or melt and drip into the underlying snow pack (Barry et al. 1990). Canopy density and basal area are highly correlated with variations in snow water equivalent (SWE) in forest stands (Potts 1984a; Schmidt and Troendle 1989; Teti 2003); however, climatic conditions also play a role (López-Moreno and Stähli 2008). Climate variations determine the intensity of storm systems and related precipitation, which in turn affects the interception ability of the canopy.

The forest canopy also affects energy available for snow ablation by absorbing and reflecting incoming shortwave radiation, altering emissions of longwave radiation, and reducing snow surface albedo with organic material (Link and Marks 1999). Forest canopy reduces wind speed, resulting in shallower temperature and humidity gradients near the surface and affecting turbulent heat transfers. The canopy can also be warmed by sensible heat transfer from above, resulting in increased longwave radiation emission that may offset some of the negative energy fluxes (Woo and Geisbrecht 2000). However, there is an upper limit to warming and ablation of the snowpack by this increased longwave radiation, given the low vapour pressure gradient near the snow surface due to low wind speeds (Golding and Swanson 1986). The balance between incoming shortwave and outgoing longwave radiation thus determines whether the snowpack in a forest melts sooner than that in an opening (López-Moreno and Stähli 2008).

Pine beetle infestations open the canopy and thin dense stands of trees. Needles are lost within the first three to five years, branches within 10-15 years, and trees begin to fall five years after stand death (Mitchell and Preisler 1998), with blowdown peaking ~10 years after stand death (Huggard and Lewis 2007). While it is clear that interception by beetle-killed canopies will be altered, as the remaining branches are inefficient interceptors (Schmidt and Gluns 1991; Hedstrom and Pomeroy 1998), few studies have been conducted to determine the impacts of a dead forest canopy on snow interception (Schmid et al. 1991; Beaudry 2007; Boon 2007). Canopy-snow interactions in a beetle-killed pine stand could potentially be equivalent to that of a shelterwood (Storck et al.

2002; Woods et al. 2006) or a deciduous (Murray and Buttle 2003) forest, despite the canopy differences between them. Since the dominant solution to beetle management has been salvage harvesting, it is imperative to determine how the hydrologic response of an infested forest differs from that of a clearcut. This will factor into management decisions about landscape-scale impacts of salvage harvesting versus leaving standing dead trees, and have subsequent impacts on regional hydrology.

Previous studies of MPB and hydrology have focused largely on basin yield: annual water yield, fall low flows, monthly spring flows, instantaneous peak flows, and timing of spring runoff (Love 1955; Potts 1984b; Cheng 1989). While these studies hypothesized that differences in basin outflow between infested and control years were a function of decreased canopy interception and evapotranspiration, they provided no data to validate this assumption. Other studies have used numerical modelling techniques to examine MPB impacts on hydrology (e.g., BC Forest Practices Board 2007). As this approach requires empirical data for model calibration and validation, field data collection and a detailed understanding of hydrological processes in infested and dead forest stands is required.

While much is known about snow accumulation and ablation processes in forests versus clearings, and about the impacts of clearing size on accumulation and melt (Golding and Swanson 1986), the impact of forest disturbance (such as beetle-kill) on snow processes has had limited consideration. Forest disturbance may be more significant for hydrological processes than climate change impacts, given the major role of the canopy in driving ground snow accumulation and ablation (Link and Marks 1999). Of secondary importance is the fact that managing for forest disturbance results in a patchwork of stand types across a watershed (Pomeroy et al. 2002; Jost et al. 2007), which has implications for regional, landscape-level hydrology. This study analyzes two years of field data collected under three different canopy types to assess the impact of hydroclimatic variability and forest structure on snow processes. Field measurements of stand-scale differences at the watershed scale are then used to model hydrological changes in a landscape composed of a complex mosaic of clearcuts, regenerating and dead stands, and live stands. Results will provide baseline information for government and forest licensees to use in decision making regarding the management of the beetle infestation and its aftermath.

1.2 Study site

Three 2500 m^2 plots (alive; dead - grey attack; clearcut) were studied in the dry-cool sub-boreal spruce (SBSdk) ecozone (Meidinger et al. 1991), 50 km south of Fraser Lake, BC (53.72°N, 124.92°W) (Fig. 1). Each plot is representative of a larger, relatively homogenous forest stand. The landscape is dominated by glacial and glaciofluvial deposits, with exposed Pre-Cambrian basalts in the Fraser Lake region.

The nearest Environment Canada meteorological station operational during the study period is 70 km west of the study site, on the north shore of Ootsa Lake (54° 46.2' N, 126° 0' W; 861 m asl) (Fig. 1). Annual average (1971-2000) air temperature at this site is 3.1°C, with monthly averages ranging from -9.1°C in January to 13.8°C in July and August. Annual precipitation is 426 mm: 38% falls as snow, the majority in December and January. While most rain falls during June, it can occur in any month of the year (Environment Canada 2008).

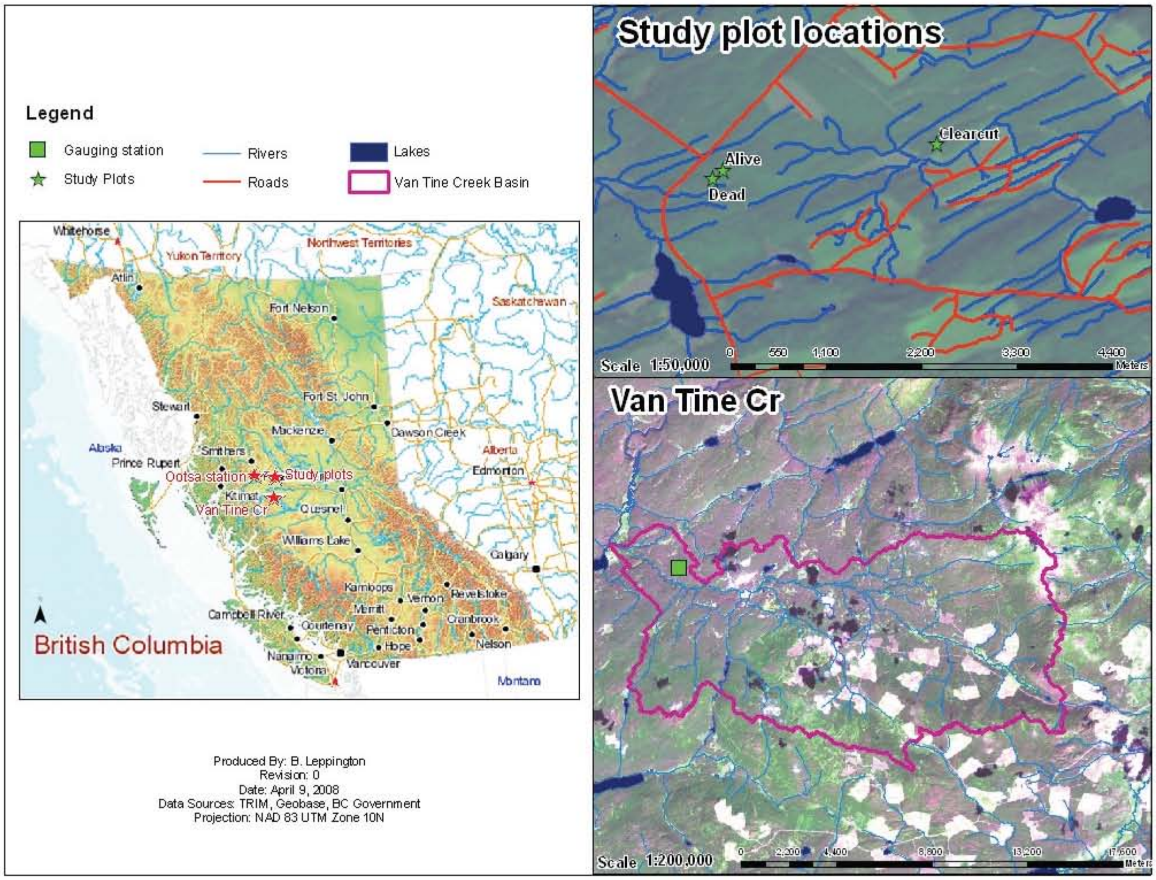

Figure 1. Study region, locations of study plots, and outline of Van Tine Creek watershed.

1.3 Study objectives

The main goal of this research is to assess the impact of MPB-killed forest and salvage harvesting on stand-scale snow ablation, and watershed-scale runoff. Four main objectives are addressed: (1) Initiate snow accumulation and meteorological monitoring in alive, dead (beetle-killed) and clearcut forest stands; (2) determine snow accumulation variability between stand types caused by both interannual variability in meteorological conditions and altered canopy structure caused by infestation; (3) determine impacts on snow ablation of snow accumulation differences and altered canopy structure caused by infestation; and (4) use results to model watershed-scale melt/runoff response to infestation and canopy reduction, and to salvage harvesting.

2 Materials and Methods

2.1 Plot layout and forest structure

Three 2500 m^2 plots were established in a dead, alive, and clearcut forest stand (Fig. 2). Each plot is marked by a 6 x 6 grid of stakes placed at ~10 m intervals. Basic forest measurements, as well as plot age and the kill date of the dead plot, were collected following provincial guidelines (BC Ministry of Forests and Range 2007), and used to assess variations in physical characteristics between plots.

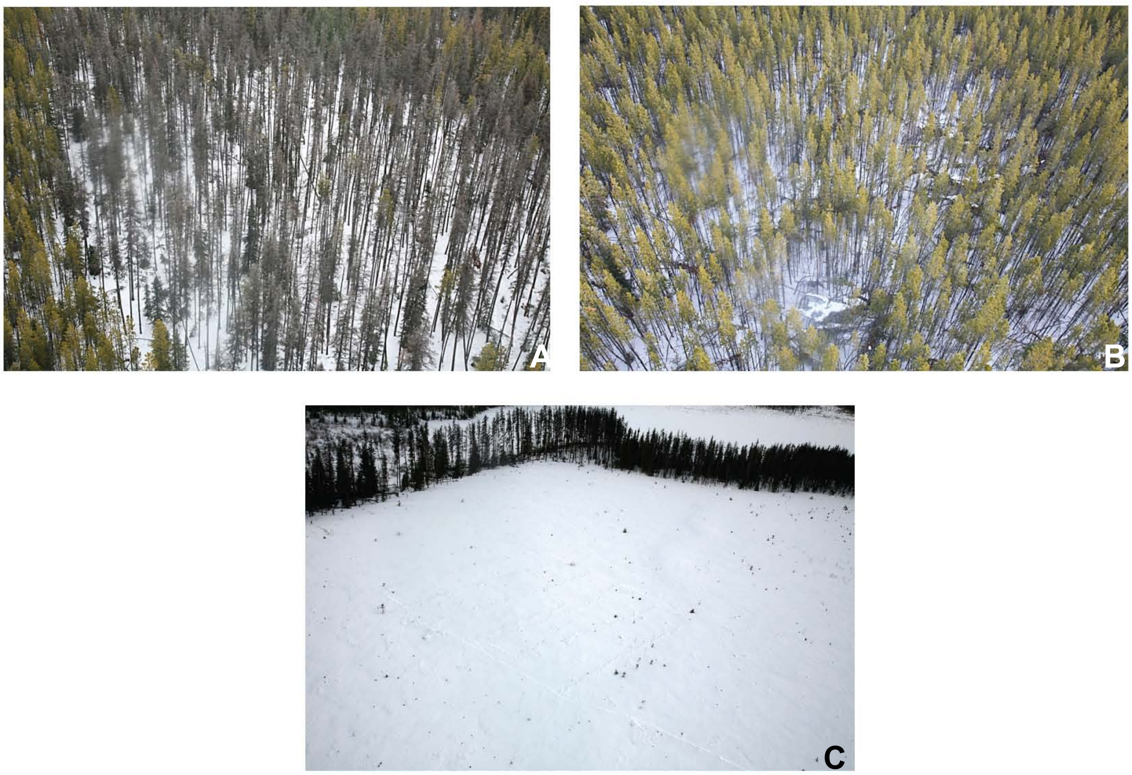

Figure 2. Aerial view of (a) dead, (b) alive and (c) clearcut stands on 14 March 2008.

Canopy structure was secondarily assessed with upward-looking hemispherical fisheye photographs of the canopy above each meteorological station and above detailed forest structure measurement plots. Images were collected using a Canon EOS 5D digital SLR camera with full-frame sensor and a Sigma 180º true fisheye lens mounted on a levelled tripod. Tripod height and the location of north were noted for each photo, as were the coordinates of each photo location. Photos were analyzed using Gap Light Analyzer v2.0, which calculates radiation transmission through the canopy based on canopy density and radiation incident at the top of the canopy (Frazer et al. 1999).

2.2 Local meteorology

Meteorological data were collected to assess micrometeorological differences between plots, and to use in modelling snow ablation and watershed-scale runoff. In November, 2006, a Campbell Scientific meteorological station was installed in the clearcut, and an Onset meteorological station was installed in the dead plot. A second Onset meteorological station was installed in the alive plot in December, 2006. The meteorological station in the clearcut monitored hourly and daily averages of one minute readings of air temperature, relative humidity, net radiation, incoming and reflected shortwave radiation, wind speed and direction, barometric pressure, and snow depth (Table 1). A time-lapse camera also monitored snowfall events and spring snow removal timing.

Stations in the dead and alive plots monitored hourly averages of one-minute readings of air temperature, relative humidity, barometric pressure, wind speed and direction, and incoming global radiation (Table 1). A sensor monitoring reflected global radiation was added to both the dead and alive stations in April, 2007.

An additional Campbell Scientific station was installed in each of the forested (dead and alive) plots in October, 2007 and March, 2008, respectively. Each station continuously monitored snow depth and air temperature for comparison with the clearcut.

Due to equipment malfunction, there are data gaps in the meteorological record from both the alive and dead plots.

Table 1. Instruments and measurement heights (in m) at each meteorological station.

	RH/Temp with shield	Barometric pressure	Anemometer	Incoming/reflected solar radiation	Net radiation	Snow depth	Air temp (for snow correction)
Clearcut	1.9	-	1.8	1.6/1.3	1.3	1.5	N/A
Dead	1.4	In logger enclosure	2.2	1.9/0.9	N/A	1.2	1.2
Alive	1.5	In logger enclosure	2.3	2.1/1.1	N/A	1.2	1.2

2.3 Snow measurements

Snow pits and snow surveys were used to assess variations in snow accumulation between plots. The field sites were visited at the beginning of each month during the winters of 2006-2007 and 2007-2008 (December - April). In each plot, a snow pit was dug and used to characterize snowpack structure, temperature, and density using standard methods (e.g., Adams and Barr 1974). Complementary snow depth measurements were collected on the 36-stake grid and multiplied by measured snow pit densities to calculate SWE (cf. Elder et al. 1991), as the presence of internal ice layers and depth hoar often precluded the collection of representative snow core samples with the standard Federal snow sampler.

Notched box-and-whisker graphs of 1 April snow depth and water equivalent were plotted to graphically assess differences between plots. Overlapping notches in the box plots suggest that the medians are not statistically different at $p = 0.05$ (Chambers et al. 1983). One-way fixed analysis of variance (ANOVA) was applied to snow depth and SWE data to determine the significance of differences between study plots (Sit 1995). Shapiro-Wilks' W test was used to confirm the normality of the data distributions

(Shapiro et al. 1968) and Levene's test was used to confirm homogeneity of variances (Lewicki and Hill 2006). Scheffe's test was used as a post-hoc analysis to identify which pairs of plots were statistically different (Hill and Lewicki 2007). Repeated-measures ANOVA was used to determine whether similar differences existed between plots in both years, or whether they differed between years (Winkler et al. 2005).

2.4 Calculating plot-level snow ablation

Point-based daily snow ablation amounts and rates in each plot were calculated using a simple 1-D energy balance model and daily averages of meteorological data:

$$Q_m = K + L + H + LE + G + R \quad (1)$$

where Q_m is the total energy available for ablation (MJ m^{-2}), K is the net shortwave radiation, L is the net longwave radiation, H is the sensible heat flux, LE is the latent heat flux, G is the ground heat flux, and R is the energy input from rainfall. Further details on this model can be found in Dingman (2002).

For K calculations, snow albedo values were calculated from field measurements of incoming and reflected global radiation. For L calculations, continuous measurements of free atmosphere and canopy temperature (T_{at}) and snow surface temperature (T_{ss}) were unavailable. Thus, T_{at} was assumed equivalent to the air temperature (T_a), and T_{ss} was calculated for each plot using a linear regression of measured values of T_a and T_{ss} from each snow sample period. To calculate the emissivity of the atmosphere and forest canopy (ε_{at}), values of canopy density (F; in %), atmospheric vapour pressure (e_a; in kPa), and degree of cloud cover (C; in %) were required. F values were determined from fisheye photos and e_a was calculated using T_a and relative humidity. C was calculated as a ratio of measured to potential daily clear-sky maximum shortwave radiation in the clearcut, and was verified with time-lapse imagery from the clearcut.

Values for ground heat flux were considered zero in the clearcut and dead plots, as the ground was observed to be frozen during snowpack measurements. In the alive plot, however, the ground did not freeze over winter, thus the ground heat flux was set to a constant value of 0.86 MJ m^{-2} d^{-1} (Gold 1957).

Values for rain flux were assumed to be zero, as previous studies in BC have indicated that it has a minimal impact on snow ablation relative to the radiative and turbulent heat fluxes (Winkler 2001).

In each plot, K, L, H and LE were calculated using daily average values of meteorological data from March 3, 2007 (peak snowpack) to April 29, 2007 (measured snowpack removal) as model inputs. Melt calculations could not be completed for 2008, as the project terminated prior to the onset of ablation. Resulting 2007 values were summed to determine the total energy balance. Values were also converted to centimetres water equivalent (cm WE) and summed to ensure correspondence between calculated and measured SWE values, and to determine total ablation amounts. Actual snowpack removal dates were determined using a combination of incoming and reflected global radiation measurements in all stands, automated snow depth measurements in the clearcut and dead plot, and time lapse imagery from the clearcut. Average melt season ablation rates (mm d^{-1}) were calculated by summing daily ablation values and dividing them by the total number of ablation days.

In the absence of direct measurements of snow melt, model results were validated by comparison of calculated and measured SWE on 8 April, and comparison of calculated SWE with the continuous snow depth record from the clearcut. Model performance was also assessed by comparing modelled net radiation ($Q^* = K + L$) with measured Q^* in the clearcut, using both the correlation coefficient (r^2) and root mean square error (RMSE).

2.5 Modelling watershed scale spring runoff

The HBV-EC hydrological model was used to assess the impacts of forest disturbance on spring snow melt runoff at the watershed scale. The original HBV is a semi-distributed, deterministic model that divides a watershed into elevation bands, and further subdivides these bands into land use zones (forest, open, lake) (Bergstrom 1995). HBV-EC includes modifications that allow the user to define multiple climate zones within a catchment area, and to incorporate a variable reservoir configuration (parallel or serial) (Hamilton et al. 2000).

The watershed used for the modelling portion of the study was Van Tine Creek. This third order, 158 km^2 watershed is located 60 km southwest of the field plots (outlet: 53º 15.8'N, 125º 24.5'W) (Fig. 1). Van Tine Creek flows east-west from the Fawnie Range to the Entiako River, with 75% of the watershed between 1000-1400 m asl. The Water Survey of Canada (WSC) has operated a discharge gauge at the watershed outlet since 1974 (#08JA014).

Van Tine Creek is in a region with limited meteorological measurements required for model input. Thus all available datasets of daily air temperature and precipitation were collated and analyzed to assess rainfall-runoff ratios between each dataset and measured discharge in Van Tine Creek (Table 2). Based on these results, model input was derived from a 10 km gridded climate dataset from Agriculture Canada (Price et al. 2000), for a node located at 53º7.2'N, 125º16.8'W; 1069 m asl, approximately 20 km southeast of the WSC gauge.

Table 2. Datasets tested for suitability as model input. The runoff coefficient (k) is calculated as average (1975-2005) annual discharge in Van Tine Creek versus average (1975-2005) annual precipitation from each meteorological dataset. The coefficient of determination (r^2) is calculated as a regression between the 30-y time series of annual discharge in Van Tine Creek versus the 30-y time series of annual precipitation from each meteorological dataset.

Dataset	Location	k	r^2 ($p = 0.05$)
North American Regional Reanalysis (NARR)	53.02ºN, 125.36ºW 1194 m asl	0.29	0.29
AgCan (ANUSPLIN) 21062	53.12ºN, 125.28ºW 1069 m asl	0.41	0.44
AgCan (ANUSPLIN) 20645	53.21ºN, 125.34ºW 1271 m asl	0.38	0.36
AgCan (ANUSPLIN) 20646	53.24ºN, 125.20ºW 1258 m asl	0.40	0.39
Environment Canada: Ootsa Lake	53.77ºN, 126.0ºW 861 m asl	0.73	0.27
Environment Canada: Fraser Lake N. Shore	54.08ºN, 124.85ºW 674 m asl	0.15	0.04

Input monthly potential evapotranspiration totals were calculated from the AgCan data using Malmstrom's (1969) equation:

$$PET_M = 40.9 * e_a^*, (T_a) \tag{2}$$

where e_a*, (T_a) is the saturation vapour pressure at the given air temperature (calculated using monthly average air temperature). Digital geo-referenced input data including BC Terrain Resource Information Management (TRIM) maps and Vegetation Resource Inventory (VRI) maps were used to identify land cover types and delineate water bodies within the study watershed. The model was parameterized based on field data from the study plots, which are representative of forest conditions within the modelled watershed.

The model was calibrated against measured discharge data from Van Tine Creek for 1975-1989, and was validated with data from 1990-2003. Several goodness-of-fit measures were used to assess the quality of modelled (Q_m) versus observed (Q_o) discharge. Average ($\bar{x}$), standard deviation (SD) and coefficient of variation (CV) were calculated for both the Q_m and Q_o datasets, and compared. Nash-Sutcliffe's efficiency criterion (NSE) was calculated with the goal of obtaining values >0.6, and ideally >0.8 (Nash and Sutcliffe 1970). Root mean square error (RMSE) was calculated with the goal of obtaining values <0.6, and mean volume error (MVE) at long term, annual, monthly timescales was calculated with the goal of obtaining values <20%.

Following successful model calibration and validation, four harvesting/infestation scenarios (Table 3) were run to assess forest disturbance impacts on spring runoff magnitude and timing. Selected scenarios were similar to those used in a previous modelling study that applied the DHSVM (Distributed Hydrology Soils and Vegetation

Model) to a larger watershed (BC Forest Practices Board 2007), thus allowing for direct comparison between study results.

Scenarios:

(1) **Baseline (1973):** A *control* scenario to derive hydrologic response in the absence of major forest disturbance, as neither harvesting nor beetle has had a significant impact on the watershed.

(2) **Harvesting only (1999):** Conditions prior to the onset of the beetle epidemic. The input land cover dataset was modified using cutblocks delineated from Landsat 7 imagery, allowing assessment of hydrologic response to forest harvesting only.

(3) **Harvesting and beetle infestation (2004):** Considered the peak of the infestation. Additional cutblocks since 1999 were delineated using Landsat 7 satellite imagery, while infested pine-leading forest stands were determined using Ministry of Forests and Range pine beetle surveys. Thus three land cover types were defined: harvested, infested, and uninfested. This allows for assessment of hydrologic response to both harvesting and infestation.

(4) **Post-infestation and salvage harvest (2017):** Conditions following infestation and salvage harvesting. Land cover datasets were modified by converting all pine-leading forest stands to harvested areas, with the exception of any ungulate winter range, riparian reserves, wildlife tree patches and Old Growth Management areas. Of these remaining areas, pine-leading stands were classified as dead, while non-pine-leading stands are classified as alive.

Table 3. Percentage of watershed forested, attacked or harvested for each scenario.

Base Year	Unharvested forest area (%)	MPB attacked area (%)	Harvested area (%)
1973	100.0	0.0	0.0
1999	93.1	0.0	6.9
2004	88.5	53.7	11.5
2017	48.9	21.8	51.1

Scenarios were run with the same input meteorological data described above, but with the altered land cover data. Model parameters were also altered based on relationships determined from field data to simulate dead versus alive stands.

3 Results and Discussion

3.1 Forest structure

The clearcut was harvested within the last decade, and contains no measurable trees (>1.3 m; BC Ministry of Forests and Range 2007). Data from the forested plots are summarized in Table 4. The canopy in both dead and alive plots is predominantly lodgepole pine (*Pinus contorta*) with a small proportion of younger hybrid white spruce (*Picea engelmannii* x *glauca*) in the sub-canopy (17% and 3% in the dead and alive plots, respectively). The dead plot shows a pulse of understory regeneration (~725 stems ha^{-1}) that is not evident in the alive plot.

Tree heights in the dead plot average 15.0 m: sub-canopy trees average 7.3 m and dominant (canopy) trees average 21.1 m. Average tree height in the alive plot is approximately 51% of that in the dead plot at 7.7 m, with sub-canopy and canopy trees averaging 6.1 and 12.1 m, respectively.

Stem density (stems ha^{-1}) in the dead plot is ~15% that of the alive plot; however, basal area in the dead plot is twice that of the alive plot. Crown diameter, crown depth, and distance from the ground to the crown base are all lower in the alive plot at 43%, 57% and 51% of dead values, respectively. However, average canopy cover from GLA calculations is greater in the alive plot (62%), compared with 46% in the dead plot.

Dendroecological studies show that trees in the dead plot died between 1986-1992, likely following the documented mid-1980s beetle outbreak (Taylor and Carroll 2003).

Table 4. Forest cover characteristics in each study plot (dead and alive).

Forest structure variable	**Dead Stand**	**Alive Stand**
	Mean *(Standard deviation)*	
Tree species	pine & spruce	pine & spruce
# of sample plots	4.0	4.0
Total trees (>1.3 m; stems ha^{-1})	1725 *(629)*	11225 *(2749)*
Total saplings (0.5 - 1.3 m; stems ha^{-1})	725 *(377)*	0 *(0)*
% Pine stems per ha	82.6 -	96.7 -
% Spruce stems per ha	17.4 -	3.3 -
Average tree height (m)	15.0 *(8.0)*	7.7 *(3.1)*
Average height of canopy trees (m)	21.1 *(3.5)*	12.1 *(1.1)*
Average height of subcanopy trees (m)	7.3 *(4.8)*	6.1 *(1.8)*
Average DBH (cm)	17.4 *(13.1)*	6.4 *(3.3)*
Total Basal area (m^2 ha^{-1})	64.0 *(0.06)*	29.2 *(0.004)*
Average crown diam (m)	2.8 *(1.5)*	1.2 *(1.0)*
Average crown depth (m)	4.9 *(2.7)*	2.8 *(1.8)*
Average height to crown base (m)	9.6 *(7.3)*	4.9 *(2.5)*
Average age (yrs)	157 *(911)*	66 *(5)*
Average canopy cover (%; from GLA)	46 -	62 -

3.2 Meteorology

3.2.1 Interannual variability

Average snow season (December-March) air temperature at the study site was compared with climate normals (1971-2000) from Environment Canada's Ootsa Lake station to place the study years into a longer term context. In 2006-07, December-March was on average 1.3ºC above normal, while in 2007-08 December-January was on average 3.0ºC below normal, while February-March were close to normal.

Records from the BC Ministry of Environment (2007) indicate that 2006-07 was a high snowpack year, with the Nechako basin at 159% of normal on 1 April 2007. In contrast, 2007-08 was an average snowpack year, with the Nechako basin at 97% of normal on 1 April 2008 (BC Ministry of Environment, 2008).

Field measurements of average air temperature in 2006-07 were on average (all plots) 1.9ºC greater than in 2007-08. The 2006-07 season had almost twice the number of days with >0ºC air temperature. These days were distributed throughout the season, whereas in 2007-08 they were clustered at the end of the season (February).

Continuous snow depth records from the clearcut plot indicate that snowpack was deeper earlier in 2006-07, with larger and less frequent snowfalls during this season. In 2007-08, however, the early winter snowpack was relatively thin, with smaller and more frequent snowfalls throughout the season.

3.2.2 Inter-plot variability

Comparison of meteorological conditions between the three plots indicates that all are driven by the same climatic conditions. The sites represent a continuum of meteorological conditions, from the alive to dead to clearcut plots. While average temperature is similar between plots, the clearcut has the greatest temperature range (-31ºC to 7ºC). The clearcut also has the greatest incoming radiation and wind speed, and the lowest relative humidity. The dead and alive plots have similar air temperature, relative humidity, incoming radiation and wind speed (Table 5). However, the dead plot is more like the clearcut in that it has slightly greater wind speed and incoming radiation. The range of incoming radiation, in particular, is greater in the dead plot than the alive plot.

Variability in each of the meteorological variables also differs between plots (Table 5). The coefficient of variation (CV) of both air temperature and relative humidity increases, while that of wind speed decreases, from the alive to dead to clearcut plots. Of particular interest is the variability in incoming radiation, which is greatest in the dead plot and lowest in the clearcut, with the alive plot in between.

Table 5. Mean, coefficient of variation (%), and range of meteorological variables measured daily in each plot during the snow season (11 Nov – 29 March of 2006-07 and 2007-08).

	Clearcut			**Dead**			**Alive**		
	$\bar{x}$	*CV*	*Range*	$\bar{x}$	*CV*	*Range*	$\bar{x}$	*CV*	*Range*
Air temp (ºC)	-6.5	-105.9	38.0	-7.0	-94.6	35.5	-6.7	-96.2	35.3
Global radiation ($W\ m^{-2}$)	58.7	79.0	227.1	13.4	98.9	58.2	10.3	97.9	38.3
Relative humidity (%)	78.9	13.5	50.9	85.1	11.2	43.4	85.3	11.5	41.8
Wind speed ($m\ s^{-1}$)	1.5	67.3	5.5	0.1	147.5	0.7	0.0	227.8	0.3

3.3 Snowpack

Repeated-measures ANOVA of 1 April snow depth and SWE shows significant differences between year and study plot (*Depth:* $p = 0.00$; $F = 11.35$; df(plot x year) = 2; df(error) = 210; *SWE:* $p = 0.00$; $F = 28.34$; df(plot x year) = 2; df(error) = 210). Thus the relationship between study plot, SWE and snow depth was analyzed separately for each year.

3.3.1 2006-2007

Assuming that the clearcut contains the maximum potential snow depth, 1 April snow depth in the dead and alive plots was 94% and 89% of maximum, respectively, in spring 2007 (Fig. 3). Although snow processes in the clearcut could be affected by snow sublimation and redistribution due to higher wind speeds (Troendle and Meiman 1984; Golding and Swanson 1986), it is assumed that slash left in the clearcut following harvesting plays a major role in snowcover retention (Murray and Buttle 2003). Additionally, the clearcut is surrounded by a fringe of trees that may reduce wind speeds across the clearcut (see Fig. 2).

Density and SWE varied by plot type, peaking in March and April in the alive plot and the clearcut, respectively (Fig. 3). In the dead plot, density peaked in April but SWE peaked in February, largely because the deeper snowpack earlier in the season offset the lower snowpack density.

Snow depth on 1 April was significantly different between the alive and clearcut plots but the dead plot was not significantly different from the other two ($p = 0.00$; $F = 6.82$; df(plot) = 2; df(error) = 105) (Fig. 5a). SWE was not significantly different between the forested plots, but both were significantly different from the clearcut ($p = 0.00$; $F = 61.3$; df(plot) = 2; df(error) = 105) (Fig. 6a).

3.3.2 2007-2008

Again, assuming that the clearcut contains the maximum potential snow depth, 1 April snow depth in the alive and dead plots was 70% and 86% of maximum, respectively, in 2008 (Fig. 4). SWE peaked in all plots in April, whereas depth and density varied between plots. Peak density was reached in April in the forested plots, and in March in the clearcut. Peak depth occurred in February in the dead plot, March in the alive plot, and April in the clearcut.

Snow depth on 1 April was significantly different between all plots ($p = 0.00$; $F = 89.5$; df(plot) = 2; df(error) = 105) (Fig. 5b). SWE on 1 April was also significantly different between plots ($p = 0.00$; $F = 37.9$; df(plot) = 2; df(error) = 105). The dead plot and the clearcut were significantly different than the alive plot ($p = 0.00$), but less significantly different from each other ($p = 0.02$) (Fig. 6b).

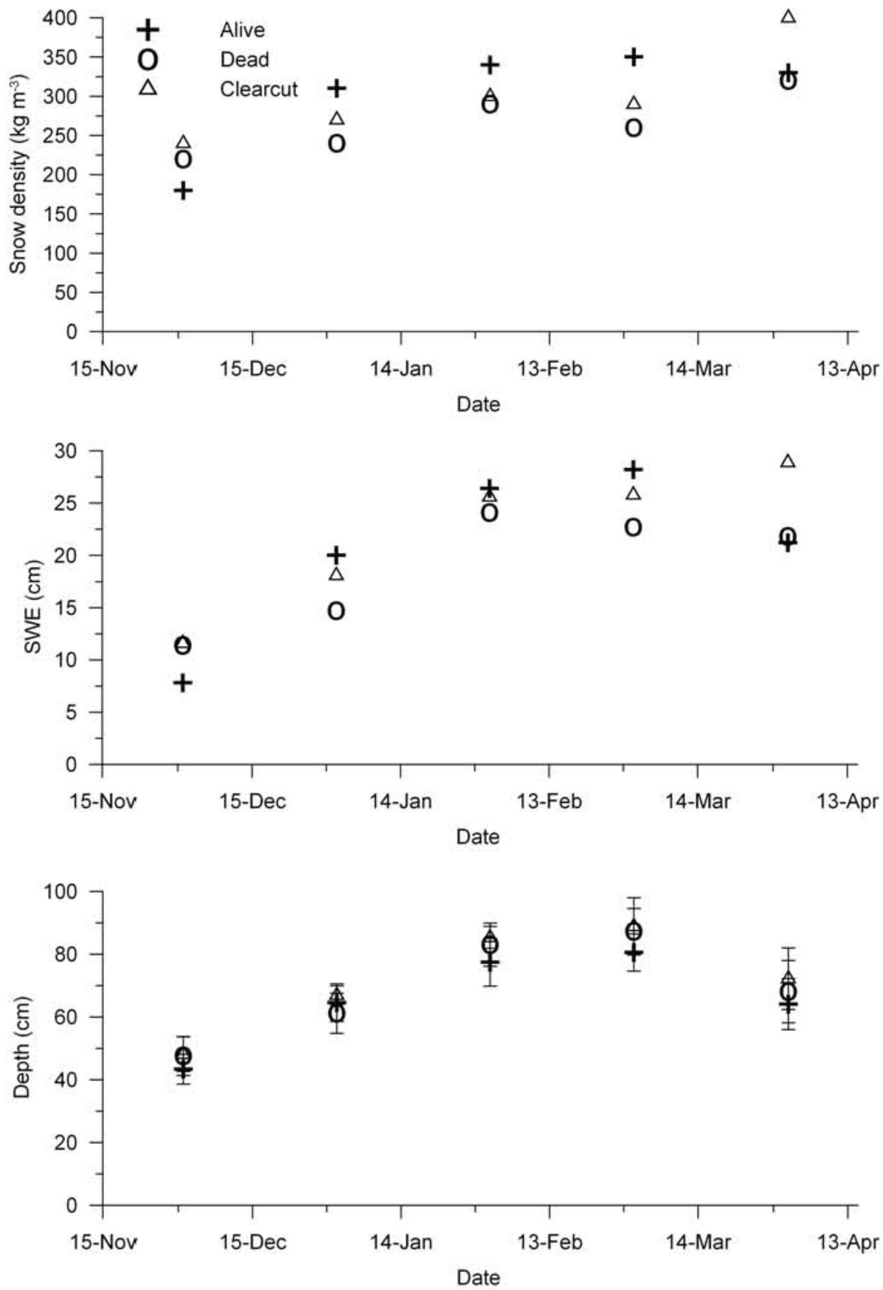

Figure 3. Snow density, SWE and depth in each stand in the 2006-07 season. Error bars on depth measurements indicate ±1 standard deviation.

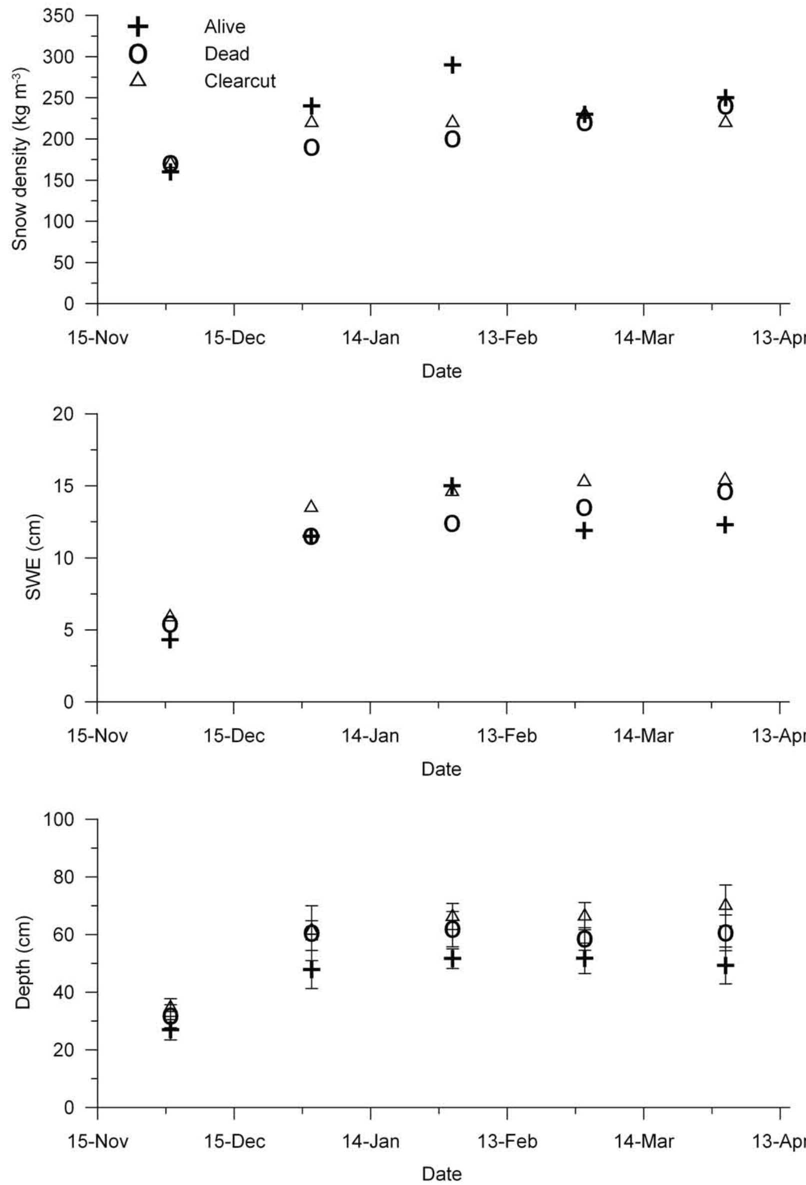

Figure 4. Snow density, SWE and depth in each stand in the 2007-08 season. Error bars on depth measurements indicate ±1 standard deviation.

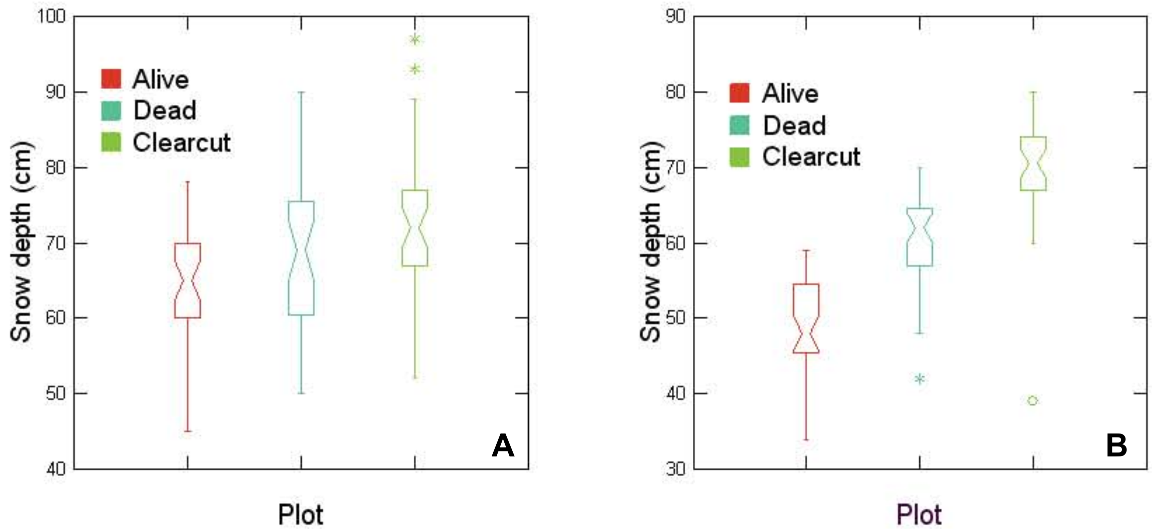

Figure 5. Notched box plots of snow depth between stands: (a) 1 April 2007 and (b) 1 April 2008. For each sample population (*n* = 36), the notch marks the median, the box ends mark the 25th and 75th percentile, and the bars show non-outlier maximum and minimum values.

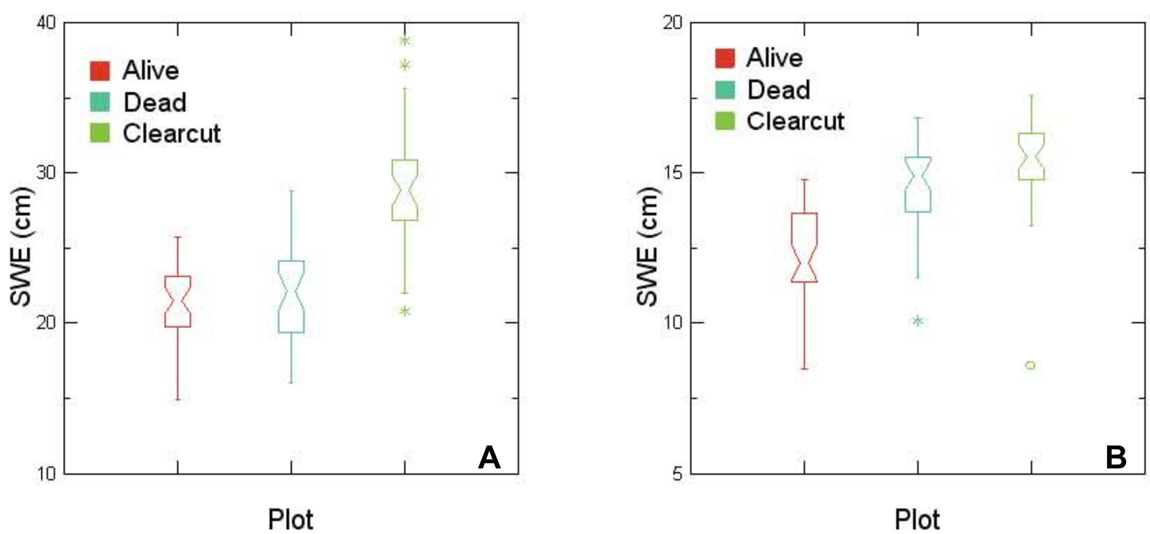

Figure 6. Notched box plots of SWE between stands: (a) 1 April 2007 and (b) 1 April 2008. See description in Fig. 5.

3.3.3 Interception

In 2006-07, plot-scale depth measurements were used to assess interception processes between stands. The similarity of peak snow depth between the forested stands and the clearcut (alive 89%, dead 94% of max) suggests that interception was minimal. Field observations determined that the forest understory did not contribute to interception due to an early-season snowfall that flattened it against the ground, leaving only the overstory for interception.

In 2007-08, plot-scale depth measurements suggest that interception was more significant (alive 70%, dead 86% of maximum). Point-based comparisons of snowfall events within the clearcut and the dead plots shows that the clearcut had a greater number of individual snowfall events, with a greater size range (Table 6). On average, 85% of each individual snowfall was intercepted by the canopy in the dead plot; this value corresponds well with the plot-wide difference in peak snow depth. While snowfalls in the clearcut were generally associated with smaller recorded snowfalls in the dead plot, on several occasions the recorded snowfall in the dead plot was larger than in the clearcut, or occurred in the absence of a similar event in the clearcut (Fig. 7).

Table 6. Characteristics of individual snowfalls in the clearcut and dead plots in 2007-08 based on continuous snow depth records.

	Clearcut	Dead
Average depth (cm)	3.4	2.8
Total number	34.0	29.0
Max snowfall amount (cm)	11.1	8.1
Min snowfall amount (cm)	1.0	0.6

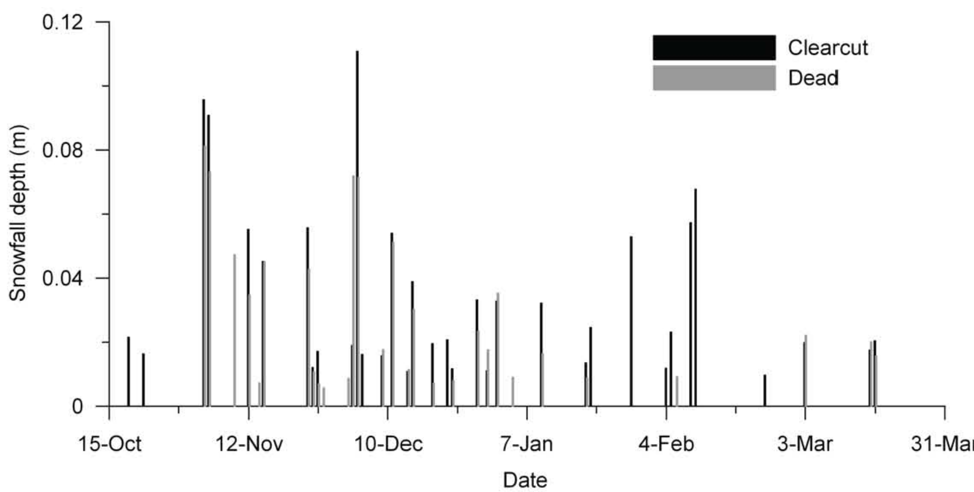

Figure 7. Individual snowfall comparison between the clearcut and dead plots during the 2007-08 winter.

3.4 Snow ablation

3.4.1 Results

In 2007, snowpack in the alive plot began warming on 3 March, 34 days prior to a net positive energy balance in the other plots (Fig. 8). The net energy balance was insufficient to initiate ablation until 5 April in the alive plot, and 6 April in the dead and clearcut plots.

Ablation duration was longest in the clearcut and shortest in the alive plot, with the dead plot midway between the two (Table 7; Fig. 9). Ablation rates were lowest in the dead plot and greatest in the alive plot, with the clearcut in between. Ablation rates in the dead plot were 7% and 10% less than those in the clearcut and alive plot, respectively. Ablation rates in the alive plot were 3% greater than those in the clearcut.

Net shortwave radiation was lowest in the alive plot and greatest in the clearcut, while net longwave radiation followed the opposite trend: greatest in the alive plot but lowest in the clearcut (Table 8; Fig. 10). Although the turbulent fluxes were an order of magnitude greater in the clearcut than in the forested stands, they followed similar trends in the dead plot and the clearcut. The energy balance in the dead plot was dominated by positive net shortwave and negative net longwave radiation, while in the alive plot both were positive. Energy balance conditions in the clearcut were dominated by net shortwave and sensible heat flux, and an extremely negative net longwave flux.

Table 7. Calculated and measured ablation conditions (spring 2007) in each study plot.

Study plot	**Date of ablation start (calc)**	**Date of snow removal (calc)**	**Date of snow removal (meas)**	**Ablation duration (days; calc)**	**Ablation rate (mm d^{-1})**
Open	6 Apr	29 Apr	29 Apr	24	12.8
Dead	6 Apr	26 Apr	26 Apr	21	11.9
Alive	5 Apr	21 Apr	19 Apr	18	13.2

Table 8. Net values of each energy balance component (in MJ m^{-2}) during the 2007 melt period (6-29 April).

Study plot	**K**	**L**	**SHF**	**LHF**	**Net**
Open	153.8	-101.6	65.0	-14.4	102.9
Dead	97.0	-17.8	4.2	-0.3	83.1
Alive	51.2	4.3	0.7	-0.2	56.0

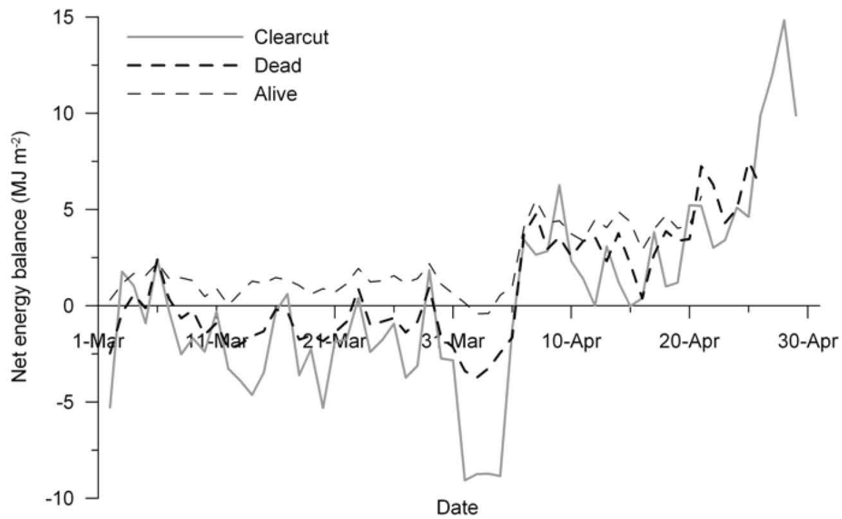

Figure 8. Net energy balance in each plot during the 2007 ablation season. Note that net energy balance does not become positive in the dead and clearcut plots until 6 April.

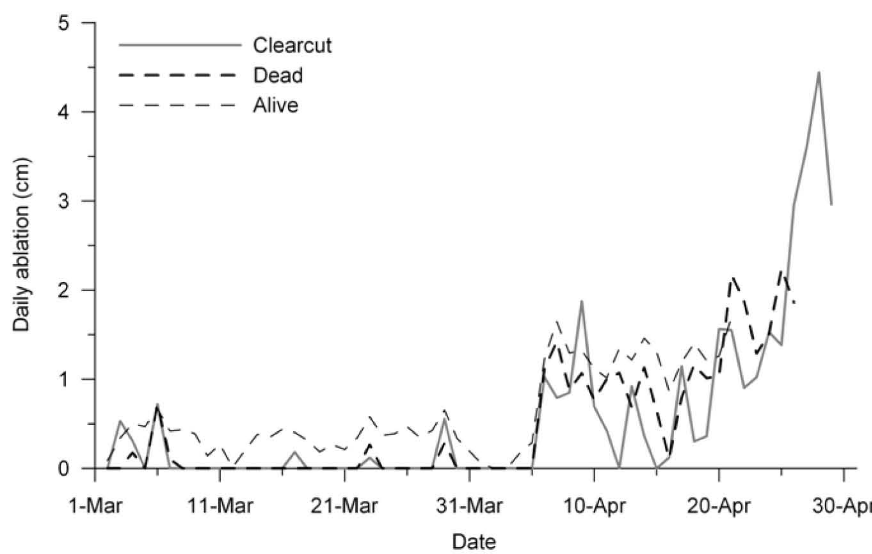

Figure 9. Calculated daily ablation in each plot during the 2007 ablation period from the 1-D energy balance model.

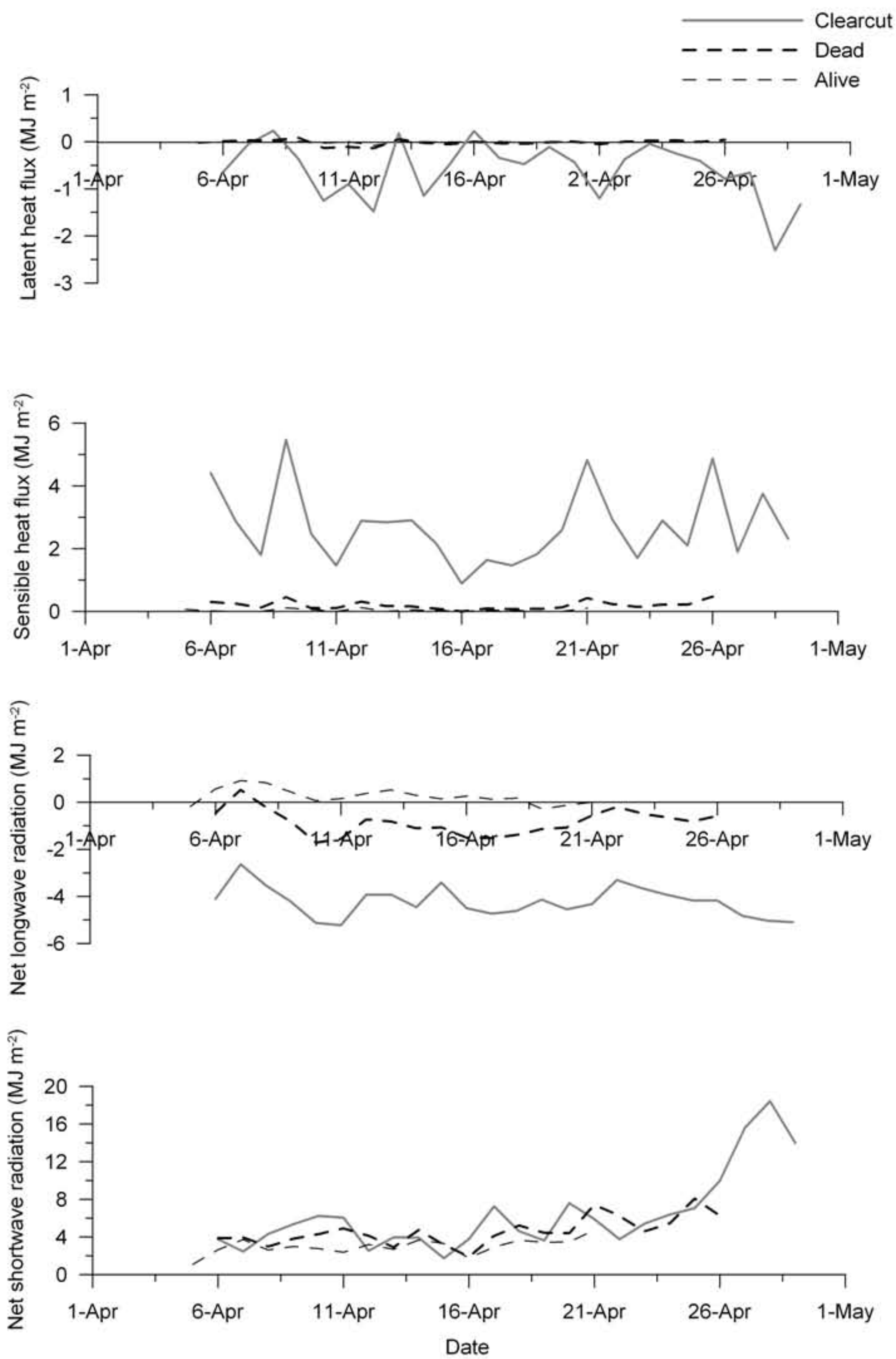

Figure 10. Individual energy balance components in each plot from 1-D model calculations.

3.4.2 Error assessment

Model output matched well with observed conditions; correspondence was improved by increasing the canopy density value for the dead and alive plots. The SWE depletion curve for the clearcut correlated well with the continuous snow depth record from the same location (r^2 = 0.76; p = 0.00). However, it is difficult to compare depth directly with SWE given snow density variations over the melt season, and there are insufficient density measurements to convert depth to SWE.

Comparison of modelled versus measured SWE from 8 April gives an error of -6% in the clearcut and -2% in the dead plot, indicating that the model slightly overestimates melt. However, the dates of snowpack removal in both the clearcut and dead stands were the same between the model and field observations. The alive plot, however, had an error of -24%, with a difference of two days between observed and measured dates of snowpack removal.

Comparison of modelled Q^* ($K + L$) with measured Q^* from the clearcut indicates good correspondence (r^2 = 0.68; p = 0.00). However, the EBM consistently underestimates Q^* during the warming/ripening phase and overestimates during the melt period, resulting in an RMSE of 2.6. This explains the overestimation of daily melt, although calculated snowpack removal corresponds with field data from each plot.

Model error is partially a function of patchy snow cover removal (Murray and Buttle 2003). Although the snow had disappeared directly below the radiation sensor, reducing albedo to snow-free values, snow cover was likely still present away from the sensor. Similar conditions were observed in the time lapse imagery from the clearcut. Additional error could result from incorrect parameterization of turbulent fluxes – partitioning into periods with stable and unstable boundary layer conditions (e.g., Moore 1983) may improve melt approximations.

3.5 Watershed runoff

Watershed modelling was limited by the quality of the input meteorological data, and subsequent difficulty in obtaining an accurate baseline model representation of the Van Tine Creek watershed. Goodness-of-fit measures indicate several large differences between observed and modelled data that could not be improved (Table 9).

Table 9. Goodness-of-fit measures between observed and modelled discharge in Van Tine Creek for the calibration dataset (1990-2003).*

	$\bar{x}$ ($m^3 s^{-1}$)	SD	CV	NSE	RMSE	MVE (annual; %)
Observed	0.8	1.3	1.6	0.6	0.8	35
Modelled	0.8	1.2	1.5			

*Optimum fit: NSE > 0.6, RMSE < 0.6, MVE < 20%

Additionally, while model output shows minimal difference between the 1973 and 1999 scenarios because the percentage of the watershed harvested is insufficient to generate major variations in streamflow, results of the 2004 and 2017 scenario runs cannot be physically explained. This suggests an error in either the model parameterization or land cover information that must be further examined to assess model suitability for these calculations.

3.6 Discussion

The dead plot is in an old growth stand (approximately 157 years old) that died between the early 1990s and early 2000s. Prior to death, the stand passed the stem exclusion stage with a subsequent decrease in tree density, the growth of taller, larger trees, and an increase in understory. Following stand death there has been an increase in understory growth due to reduced competition for resources, as evidenced by the greater understory in the dead relative to the alive plot. While the dead plot has a greater crown diameter and depth than the alive plot, the crown is composed only of branches, and in many cases the tree leader has broken away. The alive plot (66 years) is at an earlier successional stage, with continuing competition and colonization leading to high density/low basal area, and little to no understory growth. The trees are shorter on average with a smaller diameter at breast height (dbh), smaller crown diameter and depth, and with crown bases closer to the ground surface.

These structural attributes suggest that forest disturbance plays a major role in driving interception and ablation processes (Link and Marks 1999). Tree crowns in the dead plot are less able to intercept incoming snowfall, while the regenerating understory is too short and weak to make up for the interception decline. In the alive plot, however, the high stem density and the inclusion of live needles in the canopy structure greatly enhances canopy available for snow interception. Additionally, the proximity of the canopy base to the snow surface enhances longwave radiation transfer during the ablation season.

Research results corroborate studies indicating that climate conditions – in addition to canopy structure – affect snow accumulation between forest types. López-Moreno and Stähli (2008) found that the percent snow in the forest relative to the open was a function of climate, and reached a maximum under warm/wet climate conditions. Other studies have shown that snow depth differences between forested and cleared areas are minimal in years with high snowfall (Storck et al. 2002; Stähli and Gustafsson 2006; Woods et al. 2006).

Continuous snow depth measurements in the dead and clearcut plots indicate that smaller snowfalls, and a proportion of each large snowfall, are intercepted by the dead forest canopy, reducing the range of individual snowfall amounts relative to the clearcut. The accumulated snow is released, however, when it exceeds the canopy's storage capacity (Hedstrom and Pomeroy 1998).

Interception and subsequent release from canopy storage results in: (1) a lower frequency of recorded snowfall events in the dead plot than in the clearcut; (2) recorded snowfalls in the dead plot that don't appear in the clearcut (i.e., unloading of canopy storage); and (3) in some cases, a larger recorded snowfall in the dead plot than the clearcut (interception storage exceeds a threshold value and is released). In the alive plot, the higher canopy density likely results in the interception of a greater number and greater volume of snowfalls, particularly since it has maintained its needle structure (Schmidt and Gluns 1991).

These interception processes drive differences in snow depth and SWE between plots. In 2006-07, a year with less frequent, large snowfalls, the forested plots were statistically different than the clearcut, but not from each other. Forest canopy interception played only a small role, as the magnitude of seasonal snowfalls overwhelmed canopy storage capacity, resulting in similar accumulation between the forested plots. SWE was largely density driven, due to the relatively invariable snow depth. This is particularly true in the forested plots, where canopy drip and release of melting snow masses following major snowfalls would play a significant role in snow densification (Barry et al. 1990) not seen in the clearcut.

In 2007-08, however, a year with smaller, more frequent snowfalls, all plots are statistically different from each other. Canopy in the forested plots is better able to intercept snow, and less likely to exceed storage capacity. In such years, SWE is largely depth driven, particularly in the clearcut and dead plots, where density variations over the season were minimal. Thus a beetle-killed canopy plays a larger role in altering ground snow accumulation in average and low snow years, when dead stands will have greater snow accumulation than live stands, but still less than in clearcuts. In high snow years, however, heavy snowfalls may override any canopy differences between forest types.

Results compare well with other studies that find greater SWE in openings versus forested stands (Murray and Buttle 2003; Stähli and Gustafsson 2006; Storck et al. 2002). While the magnitude of measured differences between open and forested stands varies from 33%-50% less in the forest (Stähli and Gustafsson 2006; Hardy and Albert 1995), these studies do not address the differences between forest canopy types that are important for this research.

Below-canopy meteorological conditions are important in determining the energy available for snow ablation. Wind speed, air temperature, and relatively humidity in the dead plot are closer to conditions in the alive plot due to the impact of tree canopy in reducing wind speeds and providing shade, which reduces air temperatures. However, incoming radiation in the dead plot falls between the clearcut and alive plot. Thus the magnitude of the sensible and latent heat fluxes in the dead plot is similar to the alive plot, but the dead plot has greater energy inputs from shortwave radiation than the alive plot.

Energy balance model results validate these assumptions. Snow ablation in the dead plot is driven largely by shortwave radiation, as longwave radiation is highly negative given the low stem density. While the turbulent fluxes do not play a major role, they follow the same trend as in the clearcut, not as in the alive plot. Given the age of the dead plot, it’s likely that ablation may never reach clearcut conditions, as the stand has already passed peak blowdown and regeneration will continue (Huggard and Lewis 2007). The dead plot is currently the closest it will come to clearcut conditions; as it continues to age, the increasing growth of the understory will eventually return the canopy to alive stand conditions.

In contrast, ablation in the alive plot is driven largely by warming of the canopy and subsequent longwave emissions. This is enhanced by the number of stems that are parallel, rather than perpendicular, to the ground surface (Woo and Giesbrecht 2000), following snow loading and blowdown from an abnormal early season snowfall (~1 m of wet snow over 24 hours in mid-October, 2006), and a series of windstorms over the 2006-07 winter. The enhanced longwave is the main contributor to snowpack warming and ripening; the increased contribution from shortwave radiation after 5 April results in an ablation rate greater than in the other two plots.

Ablation rate variations between plots are a function not only of melt energy, but of the duration of the ablation period. While ablation rates are largely found to be greater in open areas, ranging from 30%-300% greater than in forested stands (Pomeroy and Granger 1997; Murray and Buttle 2003; Winkler et al. 2005; López-Moreno and Stähli 2008), the greatest difference in forest versus open ablation appears to occur in stands with a combination of relatively low SWE but high ablation energy (Faria et al. 2000). This is similar to the alive plot: ablation energy is available from greater longwave advection by trees during positive air temperatures, and lower snow surface albedo due to forest litter (López-Moreno and Latron 2008).

The ablation rate was lowest in the dead plot: although there was more energy available than in the alive plot, there was more SWE to remove. Ablation rate was greatest in the alive plot: although there was less energy, there was less SWE to remove and the ablation period was longer. Energy balance calculations indicate that the alive plot was the first to become snow free, on 21 April. The dead plot followed on 26 April, and the clearcut was last on 29 April. Despite a greater ablation rate than the dead plot, the clearcut had the longest snow cover duration due to the volume of SWE to be removed. In the forested stands, progressive snowpack removal during the ablation period allows saplings and shrubs to emerge from under the snowpack. These contribute to enhanced melt through increasing surface roughness and decreasing albedo, and through increased longwave emissions. The patchy snowpack resulting from this vegetation exposure also allows for heat advection from bare to snow-covered patches, speeding the removal of snow in the forested plots (Metcalfe and Buttle 1998).

Results show that beetle-killed forests must be considered a separate forest type when assessing canopy impacts on snow accumulation and ablation. It is likely not possible to compare snow accumulation and ablation in dead stands with similar processes in shelterwood or deciduous forests, as the canopy differences can be substantial. The dead pine canopy has horizontal branches in a ~1.4 m radius around the stem, limited to the top 5 m of a 15 m tree. In contrast, deciduous canopies have a greater density of branches largely oriented ~80º from horizontal, which are closer to the ground surface (Hutchison et al. 1986). Finally, shelterwood canopies have reduced canopy density, but the remaining canopy retains needles required for efficient snowfall interception. Snowfall interception in an evenly thinned shelterwood forest is closest to that in an unthinned alive forest, while interception in a deciduous forest is expected to be closer to a clearcut given branch orientation. Dead stands likely fall between shelterwood and deciduous canopies, depending on the time since stand death and the subsequent volume of needle and fine branch loss.

Given the failure of the watershed model, stand-scale results only suggest possible watershed-scale response. Beetle infestation will likely result in delayed spring runoff timing, as SWE in dead forest stands will increase, but the energy available to remove it is insufficient to enhance spring runoff. Following salvage harvesting, peak flows should increase dramatically due to an increase in SWE concurrent with an increase in energy available for ablation. Following stand death and/or salvage harvesting, however, regeneration in dead stands may occur more slowly than regeneration in replanted clearcuts, thus taking longer to attain pre-attack hydrologic conditions. However, given that each watershed is a complex mosaic of alive, dead and harvested stands, watershed response cannot be predicted without the aid of numerical modelling techniques, and therefore requires further research.

4 Conclusions

Due to their unique canopy structure, dead forest stands occupy a singular place in the forest structure continuum, with subsequent impacts on snow accumulation and ablation processes. The effects of canopy death following beetle infestation include:

(1) increased accumulation in dead stands relative to live stands;

(2) reduced between-stand differences in high-snow years, and greater differences in average to low snow years;

(3) impacts on local meteorology that result in lower ablation rates in dead than in live or clearcut stands;

(4) ablation dominated by shortwave radiation rather than longwave emissions (alive) or turbulent fluxes (clearcut); and

(5) longer ablation duration than in alive stands, but shorter than in clearcuts.

There is the potential for delayed runoff peaks if dead stands are left as they are, and for increased peaks following intensive salvage harvesting, but these impacts require further research with numerical modelling techniques.

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