Snow accumulation and ablation in a beetle-killed pine stand in Northern Interior British Columbia

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Abstract

This preliminary study examined the impact of mountain pine beetle (*Dendroctonus ponderosae*) infestation and subsequent canopy mortality on ground snow accumulation and ablation in lodgepole pine (*Pinus contorta*) stands. During the winter of 2005–2006, meteorological and snow conditions were measured in three stands—dead, alive, and cleared—in Northern Interior British Columbia. Variations in measured snow conditions and meteorological data between stands were assessed. Data were used in an energy-balance model to calculate snow ablation in each stand and estimate effects on meltwater production. Results showed that the dead stand no longer behaved like an alive stand, but had not yet approached cleared stand conditions. Ablation rates in the dead stand remained similar to those in the alive stand, although accumulation was closer to that in the cleared stand. The combination of a low ablation rate and increased ground snow accumulation in the dead stand resulted in a lengthened period of snowpack disappearance. In the cleared stand, however, high ablation rates were sufficient to remove the thicker snowpack earlier than in the dead stand. A multi-year study is under way at a new research site to further quantify the relationship between beetle-kill and its effect on snowpack.

KEYWORDS: *ablation, accumulation, energy balance, forest canopy, mountain pine beetle, snow.*

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Introduction

Forest structure plays a major role in forest hydrology through its impact on interception processes, net precipitation, soil moisture, and evapotranspiration, and subsequently runoff (Chang 2003). British Columbia's forests are currently undergoing rapid and significant changes in canopy structure due to the mountain pine beetle (MPB; *Dendroctonus ponderosae*) epidemic and associated salvage-logging activities. Infestation, canopy death, and subsequent salvage-logging will significantly alter hydrological processes, with potential additional impacts on geomorphic processes (landslides, erosion, and mass movement), vegetation, and aquatic ecology.

Hélie *et al.* (2005) and Uunila *et al.* (2006) synthesized available information on the impact of MPB on forest hydrology. Their reports show that the few existing studies relating MPB or other pest outbreaks to hydrological processes focussed largely on basin yield: annual water yield, fall low flows, monthly spring flows, instantaneous peak flows, and timing of spring runoff (Love 1955; Potts 1984; Cheng 1989; Moore and Scott 2005). These studies found that annual basin yield increases in MPB-infested watersheds, peaking 15–20 years after initial infestation. Fall low flows and monthly spring flows also increase, and spring runoff occurs earlier in the season (Love 1955; Potts 1984). Although these studies suggest that differences in outflow between infested and control years are a function of decreased canopy interception and evapotranspiration, they do not provide data to validate this assumption. It is therefore important to quantify the specific watershed processes driving changes in basin streamflow response.

Because a large portion of the beetle-infested area in British Columbia covers snowmelt-dominated catchments, it is also imperative to determine the impacts of beetle infestation on snow accumulation, melt, and runoff. Alteration of these variables can increase the risk of major flooding (B.C. Forest Practices Board 2007), which damages aquatic ecosystems and property. While it is possible to extrapolate potential watershed response from previous studies of canopy–snowcover interactions and harvesting impacts on hydrology, this still requires a good understanding of the similarities and differences in canopy conditions between dead stands and healthy (alive) or cleared stands.

This paper reports preliminary progress in a continuing research program designed to understand the impact of MPB infestation on ground snow accumulation and snow ablation in dead versus alive

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and cleared stands. This study hypothesizes that dead stands are a transitional stage between alive and cleared stands. Given that dead stands may remain in this transitory stage for a 5–15 year period (Huggard and Lewis 2006), it is important to address this knowledge gap. Additionally, as the proportion of dead stands relative to alive and cleared stands shifts, changes to hydrologic processes will be magnified. This will require reassessment of the role of canopy retention in maintaining snow interception processes in dead stands and the hydrologic impact of total canopy removal during salvage-logging operations.

Snow properties and meteorological conditions were measured in alive, dead, and cleared stands over the 2005–2006 winter season and analyzed to determine inter-stand variations. Snow ablation was calculated using a simplified one-dimensional energy balance model to establish potential differences in ablation between stands. Results were used to assess how snow accumulation and ablation properties in the dead stand relate to conditions in the alive and cleared stands.

Methods

Study Site

The study site is located 50 km southeast of Vanderhoof on the Nechako Plateau in Northern Interior British Columbia (53°50' N, 123°48' W; Figure 1). This area lies within the moist-cool Sub-Boreal Spruce (SBS) biogeoclimatic zone. Dominant tree species include lodgepole pine (*Pinus contorta*), hybrid white spruce (*Picea engelmannii* × *glauca*), and subalpine fir (*Abies lasiocarpa* Nutt.), as well as trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*). Black spruce (*Picea mariana*) may also occur in wetland areas (Meidinger *et al.* 1991). Local topography is moderately rolling, with prominent esker and kettle features (Farstad 1976) and lacustrine Vanderhoof soils (V2/L) overlying glacial till.
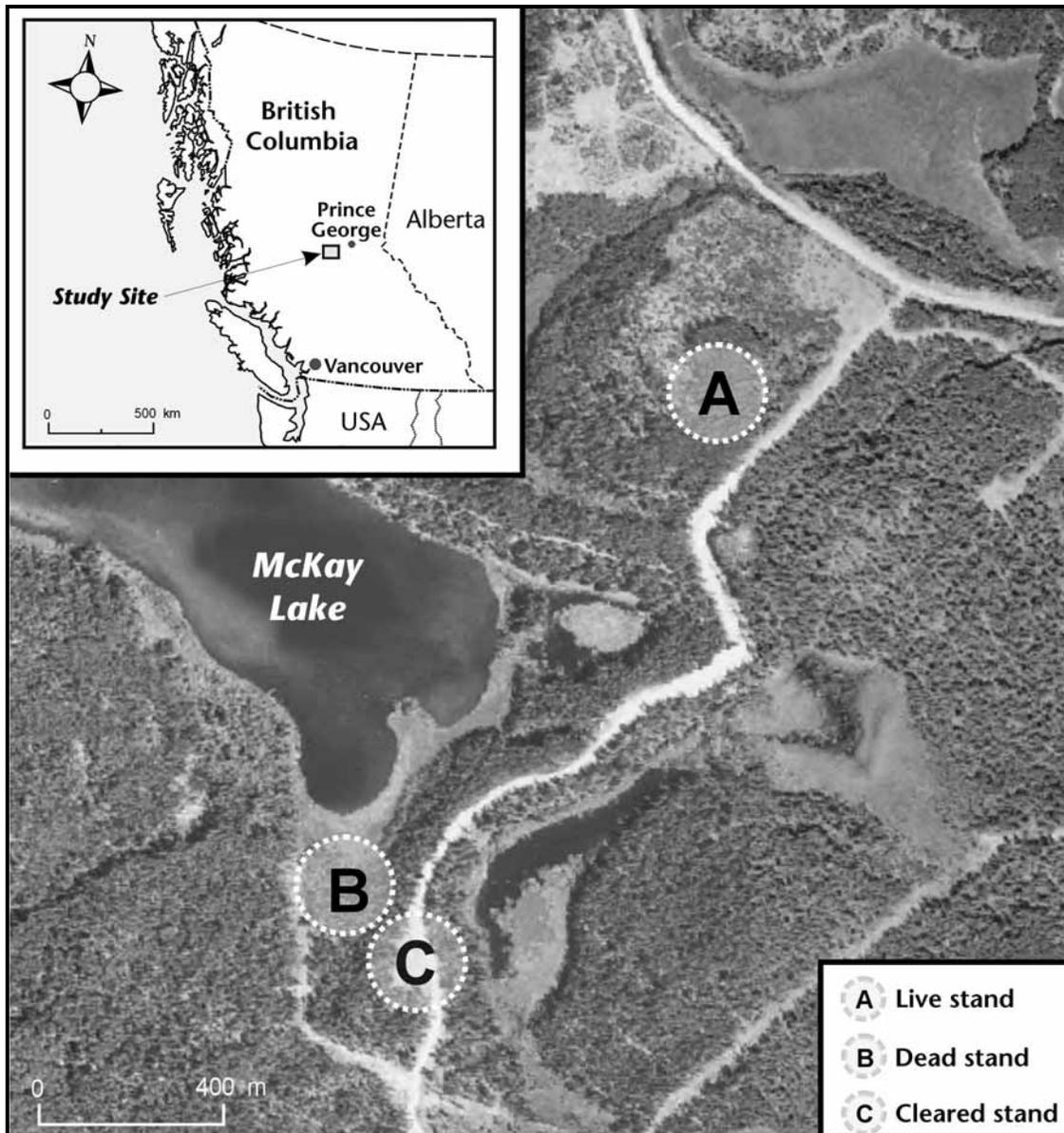
FIGURE 1. Location of study area and three selected stands.

Annual average air temperature recorded at Vanderhoof is 4.5°C (1971–2002 data; Environment Canada 2004). Mean daily air temperatures range from a minimum of –13.9°C in January to a maximum of 23.4°C in July. Average annual precipitation at Vanderhoof is 496 mm, of which 33% falls as snow.

River discharge in the SBS zone is characterized by a nival regime in which a snowmelt-driven flood peak occurs in spring (mid-March to early June). The timing of both melt onset and peak flow magnitude is directly related to end-of-winter snowpack depth and snow water equivalent (SWE), local meteorological conditions, and regional watershed characteristics (Moore and Scott 2005).

Selection of Study Stands

Aerial and land-based surveys in January 2006 were used to identify the Vanderhoof region as most likely to contain a range of both beetle-killed and alive pine stands. Three 2500 m^2 stands within a 5 km radius were selected to represent the major stages of MPB

TABLE 1. Location, species mix, age, and canopy density in each representative forest stand

	Alive	Dead	Cleared
Elevation (m)	822	828	845
Species (% of total stems)	100% lodgepole pine	70% lodgepole pine 20% hybrid white spruce 10% Douglas-fir	100% lodgepole pine
Average age (years)	35	100	10
Canopy cover (%)	80	65	< 5

infestation: alive, dead (red or grey), and cleared (salvage-harvested) (Figure 1). The alive and cleared stands represent the extreme endpoints of the canopy continuum; the dead stand represents an intermediate stage whose specific condition varies depending on time since stand death. Each stand was representative of the larger-scale surrounding forest characteristics (Table 1). The dead stand contained 70% grey/red pine and 30% red pine, with some blowdown observed. A developing understorey of Douglas-fir (*Pseudotsuga menziesii*) and hybrid white spruce was concentrated on the south end of the stand. The alive stand had minimal understorey. The cleared stand was logged in approximately 1995 and is now rangeland. A second aerial survey was conducted in March 2006 to confirm canopy composition in each stand and to obtain an aerial view of snow distribution in the region at the onset of spring melt.

Meteorology

An Onset® Weather Station was installed in the approximate centre of each stand from January 31 to April 15, 2006. Each station recorded half-hourly average values of 1-minute readings of shielded air temperature and relative humidity, global solar radiation (incoming direct and diffuse shortwave radiation), and wind speed and direction. Station locations were chosen as representative of overall stand conditions.

Snowpack

Snow pits were dug and snow characteristics analyzed bi-weekly in each stand, resulting in five surveys of the study site (snowpack was entirely removed by the sixth survey). Snow layers were identified within each pit, and the depth, density, and crystal size/type of each layer were recorded using standard snow science equipment (e.g., Elder *et al.* 1991). The vertical temperature profile

was measured in each snowpit using a series of dial thermometers inserted at 5-cm intervals starting at the base of the pit. A thermometer was also placed on the snow surface to measure snow surface temperature (T_{ss}). These data gave information on snow depth, density, and SWE over the time frame of the study, as well as the proximity of the snowpack to the 0°C isotherm. Data were also used to determine meteorologically driven snowpack differences between sites, and to verify calculations of ablation timing in each stand.

Snow depths were measured in the eight compass directions around each snow pit to obtain a first approximation of average local snow depth. Although this method has a significant sampling bias (i.e., measurement locations were determined by the position of the initial snowpit), it prevented excessive snowpack disturbance. However, eight depth measurements may not fully represent snow depth variability across an entire stand. Therefore, during study site surveys on March 18 (peak snowpack) and March 31, when snowpack disturbance was less of a consideration, depth was also measured at 2.5-m intervals along four 25-m transects radiating out from the meteorological station in each of the four cardinal directions. Previous research indicates that 50 samples are required to detect SWE differences between stand pairs (Winkler and Spittlehouse 1995). However, as this study examined three stands rather than a pair, the use of 44 samples was considered appropriate. These measurements provided detailed information of peak snow depth and its variability across and between stands, and were used in combination with snow-pit data to calculate peak SWE and inter- and intra-stand SWE variability. The use of a single density measurement was also considered appropriate. Studies covering a much larger area (e.g., 1910 ha) with greater relief used a similar technique with good results (i.e., Molotch *et al.* 2005).

Snow Ablation

Point-based daily snow ablation amounts and rates for each stand were calculated using the energy balance equation and daily averages of meteorological data:

$$Q_m = K + L + H + LE + G + R$$

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 estimated from field observations of snow surface conditions, U.S. Army Corps of Engineers (1956) snow depletion curves, and Male and Gray (1981). Snow albedo values were also used as a tuning parameter to ensure correspondence between measured and calculated SWE. For L calculations, con-tinuous measurements of free atmosphere and canopy temperature (T_{at}) and snow surface temperature (T_{ss}) were unavailable. Thus, T_{at} was assumed to be equivalent to the air temperature (T_a), and T_{ss} was calculated for each stand 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. Canopy-density values were determined from aerial surveys of each stand and atmospheric vapour pressure was calculated using T_a and relative humidity. Cloud cover was calculated as a ratio of measured to potential daily clear-sky maximum shortwave radiation in the cleared stand.

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

In each stand, K, L, H, and LE were calculated using daily average values of meteorological data from March 18 (peak snowpack) to April 15 as model inputs. Resulting values were summed to determine the total energy balance. Values were also converted to metres water equivalent (m WE) and summed to ensure correspondence between calculated and measured SWE values, and to determine total ablation amounts. Snowpack disappearance dates were determined by a combination of field observations and the date at which cumulative calculated ablation reached a value equivalent to peak measured SWE. Average melt season ablation rates were calculated by summing daily ablation values and dividing them by the total number of ablation days.

Results

Meteorology

All stations exhibited the same barometric pressure patterns. This indicated that, due to their close proximity, the stations were responding to the same weather systems, and that bulk snowfall amounts were likely the same over each stand. Predominant meteorological variables driving snow ablation at the stand scale included air temperature, global radiation, wind speed, and relative humidity (used to calculate atmospheric vapour pressure).

The dead stand had a similar daily air temperature range to the cleared stand, which was somewhat lower than that measured in the alive stand (Table 2). The dead stand also had the lowest and least variable average[1] air

TABLE 2. Mean, coefficient of variation (CV; as a proportion), and range of meteorological variables measured in each stand (January 31–April 15, 2006)

	Cleared			Dead			Alive		
	$\bar{x}$	CV	Range	$\bar{x}$	CV	Range	$\bar{x}$	CV	Range
Relative humidity (%)	71.0	0.3	83.0	76.8	0.2	80.0	72.5	0.3	82.0
Air temperature (°C)	−2.7	−2.5	38.3	−3.7	−1.9	38.8	−3.3	−2.2	40.4
Global radiation (W/m^2)	195.2	1.0	943.7	40.8	1.3	491.2	42.0	1.2	570.0
Wind speed (m/s)	0.50	1.0	2.41	0.14	1.5	1.11	0.15	1.6	1.48
Wind gust speed (m/s)	1.7	9.0	11.1	0.7	1.2	5.2	0.7	1.2	5.0
Maximum daily air temperature range (°C)		10.2			21.7			21.8	

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[1]   In this paragraph, "average" refers to the period from January 31 to April 15, 2006.
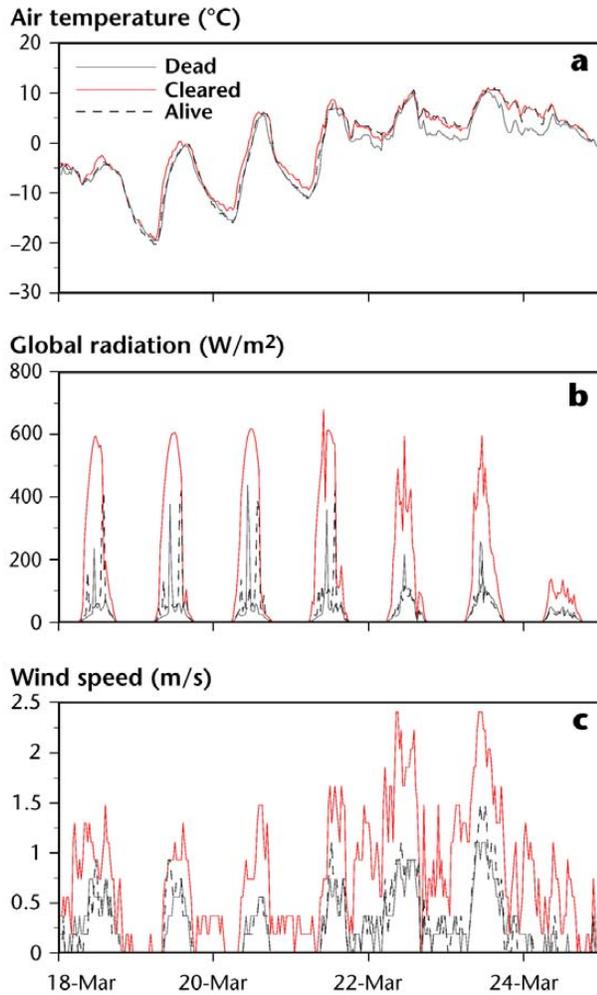
FIGURE 2. Hourly air temperature (a), global radiation (b), and wind speed (c) in each stand (March 18–24, 2006).

FIGURE 3. Snow depth (a), density (b), and snow water equivalent (c) in each stand on each sampling date. Depth was calculated as the average of eight measurements in the snowpit vicinity; density and SWE were measured in the snowpit.

temperature of all stands (Table 2; Figure 2a). Average global radiation was lowest and most variable in the dead and alive stands, while average global radiation was almost five times greater in the cleared stand (Table 2; Figure 2b). Average wind speed was lowest in the dead stand, which was similar to the alive stand, but more than three times lower than in the cleared stand (Table 2; Figure 2c). Wind gust speeds were least variable and distributed over the same range in the dead and alive stands; this range was half that of the cleared stand (Table 2). Average relative humidity was highest and least variable in the dead stand, and lowest in the cleared stand.

Snowpack

Maximum SWE occurred on March 18, as no further measurable snow amounts accumulated and average daily air temperature remained above zero after March 20 (Figure 2a). Setting the cleared stand to represent maximum possible snow accumulation, peak SWE was 47% and 27% of maximum in the dead and alive stands, respectively.

Snow depth and SWE showed the same trend between surveys in each stand (Figure 3). The exceptions were:
1. an increase in snow depth and SWE February 5–26 in the dead stand concurrent with a decrease in depth and SWE in the other two stands; and

TABLE 3. Correlation matrices for snow depth, density, and SWE in each stand (*n* = 5). The small sample size means that these values are not significant at the *p* = 0.05 level, but do serve to indicate the relationship between stands.

Stand	Depth			Density			SWE		
	Cleared	Dead	Alive	Cleared	Dead	Alive	Cleared	Dead	Alive
Cleared	1			1			1		
Dead	0.92	1		0.85	1		0.63	1	
Alive	0.92	0.95	1	0.72	0.32	1	0.00	0.48	1

2. an increase in depth and SWE March 4–18 in the cleared stand concurrent with no depth change and only a minimal SWE change in the dead and alive stands.

Between peak SWE on March 18 and site surveys on March 31, snowpack depth and SWE decreased in all stands. The greatest decrease was in the alive stand (Figure 3). While snow density increased in the cleared and dead stand, it remained relatively unchanged in the alive stand (Figure 3).

Box-and-whisker plots of SWE and snow depth showed no overlap of median values between stands (Figure 4), indicating that peak SWE and snow depth are likely to be statistically different between stands (Winkler *et al.* 2005). Correlation analysis of snow depth, density, and SWE between stands showed that while snow depth in the dead stand is most correlated with the alive stand, density and SWE in the dead stand are most closely correlated with the cleared stand (Table 3).

Snow Ablation

For the ablation calculations, canopy density (*F*) was taken from Table 1. Cloud cover proportion (*C*) was calculated from measurements in the cleared stand and ranged from 0 to 0.56, with an average of 0.11. Initial albedo values were set to 0.80 on March 18 (U.S. Army Corps of Engineers 1956), as all stands had a fresh snowfall with minimal surface debris and no vegetation showing through. Over the ablation period, albedo values decayed to 0.20, representing ground surface exposure (Male and Gray 1981).

The model successfully predicted that all stands were snow-free by April 15, corresponding with field observations. Comparison of calculated and measured SWE on March 31 showed a slight underestimation in the dead stand (12%), but strong correspondence in the alive and cleared stands (1% underestimate and 1% overestimate, respectively) (Table 4). While the one-dimensional energy
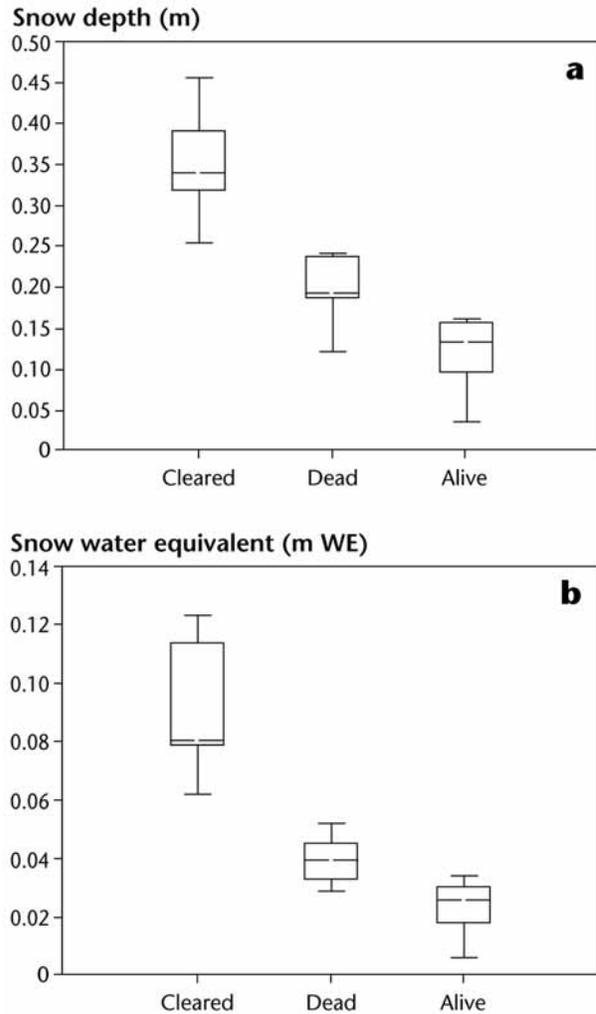
FIGURE 4. Box and whisker plots of snow depth (a) and snow water equivalent (b) in each stand on March 18, 2006. Note that March 18 was the date of peak snowpack. Graphed values are based on snow pit density measurements and snow depth transects (*n* = 44 in each stand). In each plot, the box indicates 25th and 75th percentile of the data set, the line represents the median value, and the two "whiskers" represent the extreme minimum and maximum values of the data set.

TABLE 4. Comparison of modelled and measured SWE values (m WE) in each stand on March 31, 2006. Note that the modelled and measured values in the alive stand differ at four decimal places.

	Modelled	Measured
Dead	0.044	0.039
Alive	0.006	0.006
Cleared	0.113	0.114

balance calculation often overestimates ablation, in this study the overestimation may be offset by:

• snow and (or) ice accumulation on the radiation sensor (observed in the field), which alters measured global radiation values and can result in cloud cover fraction being overestimated (and ablation underestimated); and,

• the use of estimated snow surface albedo values, which affects the role of shortwave radiation in ablation.

Daily values of each modelled energy flux were summed to calculate the total energy flux for each component during the melt period. Net shortwave (K) and longwave (L) radiation, as well as sensible heat flux (H), increased from the alive to dead to cleared stands (Table 5; Figure 5a–c). However, the latent heat flux (LE) was lowest in the dead stand and highest in the cleared stand (Table 5; Figure 5d).

Canopy gaps in the dead stand caused by needle drop and blowdown enhanced the role of K relative to the alive stand, while the variation in L between stands was largely due to stem density. The greater number of stems in the alive stand increased longwave emissivity and minimized energy losses to L. In the cleared stand, however, the lack of longwave emitters meant L was a substantial negative draw on melt energy.

The turbulent fluxes (H and LE) relate to variations in wind speed between stands. Winds were greatest

TABLE 5. Total energy fluxes (in MJ/m^2 per day) in each stand for each component of the calculated energy balance

	K	L	H	LE	NET
Dead	35.3	−27.5	3.2	−0.8	10.3
Alive	16.5	−6.1	2.6	−0.9	12.0
Cleared	117.8	−102.2	10.0	−3.6	21.9
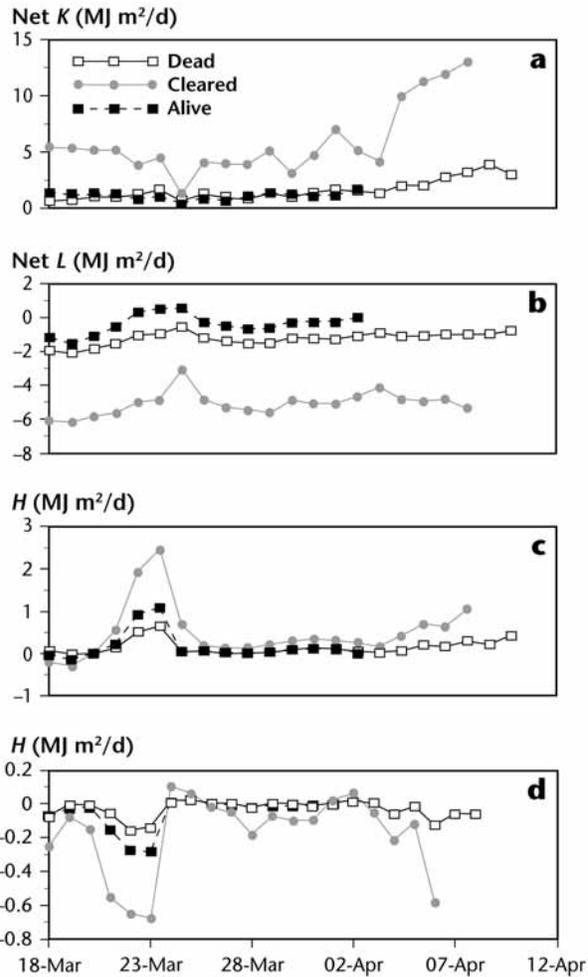
FIGURE 5. Calculated fluxes of shortwave radiation (a), longwave radiation (b), sensible heat (c), and latent heat (d) in each stand over the study period.

in the cleared stand, thus H and LE were also greatest (Figure 5c–d). Both H and LE were relatively low in the dead and alive stands. Thus, ablation in the dead stand was driven by a combination of L and K; ablation in the alive stand was driven mainly by L; in the cleared stand, ablation was driven by K, H, and LE.

From the time of peak snowpack, daily ablation amounts increased (Figure 6). The dead stand was calculated to have been snow-free on April 8, compared with April 6 in the cleared stand and April 1 in the alive stand. This corresponds with field observations from March 31, when the alive stand was almost snow-free, and April 15, when all stands were snow-free. Using March 18 as the maximum SWE date, ablation period durations were calculated as 22 days in the dead stand, 20 days in the cleared stand, and 15 days in the alive
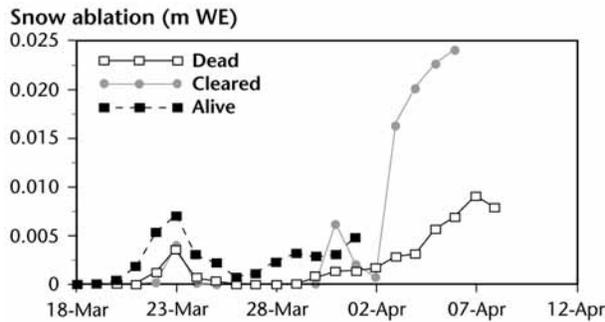
FIGURE 6. Calculated daily ablation amounts in each stand.

TABLE 6. Calculated values for dates of snowpack disappearance and ablation rate in each stand

Stand	Snowpack disappearance	Duration of ablation period (days)	Average ablation rate (m WE/day)
Cleared	April 6	20	0.0049
Dead	April 8	22	0.0021
Alive	April 1	15	0.0025

stand. The dead stand had the lowest ablation rate, which was similar to that in the alive stand but half of the rate in the cleared stand (Table 6). The longer ablation period in the dead stand was due to the low ablation rate and the deep snowpack. In the cleared stand, the higher ablation rate removed the deep snowpack more quickly, while the shallow snowpack in the alive stand resulted in the shortest ablation period.

Discussion

Variations in Snow and Meteorological Conditions

Snowpack variations between stands are attributed to needle loss and some blowdown due to beetle-kill. All stands are on similar slopes and aspects, and are in close enough proximity to have received the same snowfall inputs. Thus, canopy cover is the main variable between stands. Although differences in canopy density can also be a function of species composition, both the alive and dead stands are dominated by pine. The dead stand also had a regenerating understorey of fir and spruce, but the increased ground snow accumulation in this stand relative to the alive stand suggests that the understorey played a minimal role in interception. The alive canopy was also observed to intercept snowfall more effectively than the dead canopy.

The dead stand had an intermediate snow depth and SWE. The high canopy density in the alive stand reduced ground snow accumulation due to interception, and decreased the percentage of maximum SWE to 27%. Due to the low canopy density in the cleared stand, interception was low and ground snow accumulation increased. Thus the cleared stand had the deepest snowpack with the highest SWE.

Bi-weekly measurements of snow depth in the dead stand corresponded most closely with those from the alive stand, suggesting that canopy interception between the stands follows a similar trend. Snowpack depth and SWE in the dead and alive stands did not increase from March 4 to the March 18 peak as much as they did in the cleared stand. This indicates that intervening snowfalls were intercepted by the canopy, resulting in reduced ground snow accumulation. Although the box-plot analysis showed that snowpack conditions in each stand are likely significantly different, bi-weekly measurements of snow density and SWE in the dead stand are more closely correlated with those from the cleared rather than the alive stand. This suggests that the processes driving these variables are similar between these two stands.

Differences in interception between the dead and alive stands are at this stage largely a function of needle loss, and to a smaller extent blowdown. They are therefore directly related to the stage of canopy death. While live lodgepole pine trees can intercept 45% of a 0.001 m WE snowfall event (Schmidt and Gluns 1991), dry dead pine needles are easily removed. This reduces their interception ability relative to live pine. The canopy cover in the dead stand therefore constitutes a transitional stage. As more needles drop and trees blow down, accumulation approaches cleared stand conditions. Once the dead stand is salvage-harvested, accumulation will be equivalent to the cleared stand. Thus, while meteorological conditions are considered more important than branch form in interception amounts (Schmidt and Gluns 1991; Gelfan *et al.* 2004), in MPB-infested regions the stage of stand death also plays a significant role.

The presence or absence of forest canopy also causes significant differences in global radiation, air temperature, and wind speed between stands (Gelfan *et al.* 2004). Global radiation is most temporally variable in the dead and alive stands, but is greatest overall in the cleared stand due to the lack of canopy cover to block and scatter incoming radiation (Sicart *et al.* 2004). While daily air temperatures have a greater range in the dead and alive stands due to the effects of canopy shading, the high

incident global radiation in the cleared stand increases sensible heating, thus increasing air temperatures overall. Because of the reduced surface roughness of the cleared stand relative to the two forested stands, sustained high winds are more common. Lower and more variable wind speeds in the dead and alive stands are not only due to increased surface roughness, but also to the interaction of the canopy with the boundary layer. Thus, changes in canopy cover will not only affect ground snow accumulation, but will have significant impacts on the meteorological conditions driving snow ablation.

Impact of Snow and Meteorological Variations on Ablation

Despite the same climatic/snow inputs over a winter season, each stand has very different snowpack conditions at the onset of spring melt, contributing to differences in melt timing and volume between stands. Varying meteorological conditions between stands also have a significant impact on ablation due to their effect on the major ablation fluxes (net shortwave and longwave radiation, sensible and latent heat).

The radiative fluxes in general are most important for ablation. In the dead stand, both net long- and shortwave radiation play an important role, and in the cleared stand, net shortwave radiation is the most significant; longwave is the main driver in the alive stand as it is emitted from the forest canopy and stems (Sicart *et al.* 2004). The low wind speeds and lower air temperatures in the dead and alive stands relative to the cleared stand reduce the role of the turbulent fluxes in these stands, which in the cleared stand are very important in driving ablation (Hardy *et al.* 1997).

Results of this study compare well with other studies that find ablation rates are lower in forested areas (Gelfan *et al.* 2004; Winkler *et al.* 2005); however, some studies have found that open areas become snow-free before areas under the forest canopy (e.g., Hardy *et al.* 1997; Koivusalo and Kokkonen 2002; Winkler *et al.* 2005), and others have found the opposite (e.g., Storck *et al.* 2002). These differences are a function of specific forest type, which affects both snow accumulation amounts and the energy available for snow ablation. They are also driven by seasonal meteorology, such as bulk snowfall amounts, air temperatures, and wind speeds. The latter two variables are also affected by canopy changes linked to MPB infestation.

Ablation rate calculations and meteorological data indicate that meteorological conditions in the dead and alive stands are very similar. Thus, at the observed stage of death, the dead stand maintains a similar energy budget to the alive stand. This supports the hypothesis that the dead stand is in a transitional phase. It accumulates more snowpack than the alive stand, but it retains a similar energy budget to the alive stand and therefore does not have the energy to ablate that snowpack rapidly. As more needles are lost and canopy gaps are created by blowdown, the energy budget of the dead stand will approach that of the cleared stand. However, it is unlikely to gain enough energy to match the cleared stand, as standing snags and understorey vegetation would continue to reduce incoming shortwave radiation and wind speeds, and the reduction in canopy would decrease emitted longwave radiation. If the dead stand is salvage-logged, it will attain the same energy budget conditions as the cleared stand. If left to regenerate without logging, it may return to both the snow accumulation and energy budget conditions of the alive stand. However, few studies have quantified growth rates and restoration of canopy in beetle-killed stands.

This study shows that stage of stand death is a significant variable requiring equal attention to the impacts of salvage-harvesting. Needle loss following tree death occurs over a 3–5 year time frame, following which branch loss and blowdown increase to peak around 10–15 years after death (Huggard and Lewis 2006). Significant regeneration may also be taking place during this time period. The canopy is therefore in a transition state for an extended period, during which it will remain necessary to understand the effects of these changes on snow accumulation, ablation, and runoff.

Continuing Research

This study calculates ablation at a point beneath differing canopy covers. Given that watersheds contain a complex mosaic of different-sized dead, alive, and cleared stands distributed across a range of elevations, slopes, and aspects, it is difficult to apply this study's results to determine watershed runoff. Each stand type will contribute to basin runoff at different scales and time frames. Additionally, the study was conducted during a low snowpack year (< 65% of normal; B.C. Ministry of the Environment 2006). In a high snowpack year, variations in snow accumulation between stands may be reduced, as heavy, persistent snow can overwhelm any canopy type. In these cases, the specific meteorological characteristics of

each snowfall event may be as significant as canopy structure for snow interception and accumulation (Schmidt and Gluns 1991).

To address some of these issues, this preliminary study has been extended with funding from the Canadian Forest Service MPB Initiative (2006–2008). Three stands south of Fraser Lake, B.C., are now under study. This two-winter study will incorporate additional hydrometeorological variability, allowing for examination of the effects of snow events on between-stand variability in depth, density, and SWE.

Results of the two-winter study will be used in two additional research projects. The first will employ LiDAR to map forest cover and determine equivalent clearcut area thresholds (Weiler *et al.* 2007). The second will model large-scale hydrological response to forest change by modifying and merging two existing hydrological models, which will improve canopy representations and subsequent interception processes (Moore *et al.* 2007). This will allow for examination of runoff effects of beetle infestation.

Conclusion

Beetle-killed stands are an important transitional stage in the hydrology of snowmelt-dominated watersheds in British Columbia. Although snow accumulation in dead stands approaches that of cleared stands, ablation rates remain similar to those in live stands and are dominated by longwave fluxes, with an increased contribution from shortwave fluxes. In dead stands, the combination of a low ablation rate and increased ground snow accumulation results in a lengthened period of snowpack disappearance. In cleared stands, however, high ablation rates driven by a combination of shortwave and turbulent fluxes are sufficient to remove the thicker snowpack slightly earlier.

This research has been expanded to incorporate more detailed site measurements and additional hydrometeorological variability, and will provide valuable inputs to new studies examining the large-scale impacts of changing snow interception and ablation on watershed hydrology.

Beetle-killed stands are an important transitional stage in the hydrology of snowmelt-dominated watersheds in British Columbia.

Acknowledgments

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Test Your Knowledge . . .

Snow accumulation and ablation in a beetle-killed pine stand in Northern Interior British Columbia

How well can you recall some of the main messages in the preceding Research Report? Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. Snow water equivalent in the dead stand is:
    A) The same as in the alive stand and greater than in the cleared stand
    B) Greater than in the alive stand and less than in the cleared stand
    C) Less than in the alive stand and the same as in the cleared stand
    D) Less than in the alive and cleared stands

2. Snowpack removal occurs first in the alive stand because:
    A) The snow has a high albedo
    B) This stand has the greatest energy available for snow ablation
    C) There is less snow to remove
    D) This stand has the highest wind speeds

3. The dead stand will achieve the same energy balance conditions as the cleared stand when:
    A) All needles are lost
    B) 40% of the trees blow down
    C) It regenerates naturally
    D) It is salvage-logged