Snowpack Structure in a Beetle-Killed Stand Compared with Live and Logged Stands

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ABSTRACT

Mountain pine beetle (MPB; *Dendroctonus ponderosae*) infestation significantly alters the forest canopy, as dead trees lose needles and branches and ultimately blow down. These canopy changes have subsequent impacts on snow interception, accumulation and melt, and are therefore of major importance to nival hydrological regimes. For the past 14 years, British Columbia (BC) has been experiencing an MPB epidemic. Given the lack of knowledge regarding beetle-snow interactions, a pilot study was conducted on the Nechako Plateau near Vanderhoof, BC to examine the impact of canopy change due to beetle infestation on snow stratigraphy and metamorphism in beetle-killed versus alive and cleared stands. Bi-weekly snow pit data were collected in each of these three stand types, and differences in snow properties examined in the context of stand-specific meteorological data and physical stand properties. Results indicate that alterations in stand-scale snow accumulation and meteorology due to beetle kill affect snowpack evolution over the winter season. Originally assumed to mimic clearcuts, dead stands actually represent a key transitional stage that is initially similar to a healthy live stand, yet approaches cleared stand snow structure over the season and with increasing time since stand death. Despite the same meteorological inputs over a winter season, each stand has a very different snowpack structure at the onset of spring melt, likely contributing to differences in melt timing and volume between the stand types.

Keywords: snow; metamorphism; forest canopy; mountain pine beetle

INTRODUCTION

The mountain pine beetle (MPB; *Dendroctonus ponderosae*) is a major forest pest that has reached epidemic proportions in British Columbia, and has now crossed the provincial border into Alberta. The effects of this epidemic on canopy structure, and subsequently snow processes, can significantly alter outflow from snowmelt-dominated catchments. Canopy removal caused by infestation and death of lodgepole pine (*Pinus contorta*) affects snowfall interception amounts, altering ground snow accumulation and seasonal snow ablation, and potentially increasing runoff by up to 80% (FPB, 2007). Forest canopy changes also affect local meteorology, which plays a significant role in snowpack metamorphism and melt (Gelfan et al., 2004). MPB management practices such as salvage logging have additional impacts on snow processes. Research has shown that salvage logging could increase regional runoff by up to 92% (FPB, 2007), due to reduced snowfall interception and enhanced accumulation and ablation.

Several studies have addressed changes in basin yield under MPB conditions (e.g., Potts, 1984; Cheng, 1989; Moore and Scott, 2005). However, there remains a lack of information regarding the specific processes driving these basin yield changes, particularly in terms of snow interception and

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accumulation. In the absence of such data, some studies avoid the issue altogether by assuming that the hydrologic behaviour of beetle-killed stands is equivalent to that of cleared stands (e.g., Dobson, 2004). Recent research has shown, however, that canopy changes due to beetle kill result in significant variations in snow accumulation between stand types. The associated changes in local meteorology also cause stand-scale variations in the energy budget driving snow metamorphism and ablation (Boon, 2007). Snow processes in dead stands, therefore, occupy a continuum between those in live and those in cleared stands, depending on time since stand death. Given the lack of research in this area, quantification of snowpack processes in BC's beetle-killed forests will prepare us for changes predicted in Alberta, Canada, and allow for improved management of water resources.

The goal of this research is to examine how a beetle-killed forest canopy and subsequent changes in local meteorology drive snowpack structure in a beetle-killed (dead) stand relative to a live and a cleared stand. Three stands representing these conditions were monitored over the 2006 winter season. Results are assessed from February 2006, to peak SWE in late March 2006.

STUDY SITE

The study site is located on the Nechako Plateau in northern interior British Columbia (53° 50' N, 123° 48' W; Fig. 1). This area lies in the moist-cool sub-boreal spruce ecozone (SBSmk), within the main area of beetle infestation. Dominant tree species include lodgepole pine (*Pinus contorta*), hybrid white spruce (*Picea engelmannii x glauca*), and subalpine fir (*Abies lasiocarpa* Nutt.), as well as trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*) (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.

Three 2500 m^2 stands within a 5 km radius were selected to represent the major stages of MPB infestation: (1) dead (red/grey); (2) alive; and, (3) cleared (salvage harvested) (Fig. 1). Red trees are those that have been recently killed but still retain dead (red) needles, while grey trees are in the later stages of mortality and have no needles remaining. The alive and cleared stands represent the extreme endpoints of the canopy continuum, while the dead stand represents an intermediate stage whose specific condition varies with time since stand death. Each stand was representative of 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 understory of Douglas fir (*Pseudotsuga menziesii)* and hybrid white spruce was concentrated at the south end of the stand. The alive stand had minimal understory, and the cleared stand was logged in ~1995.

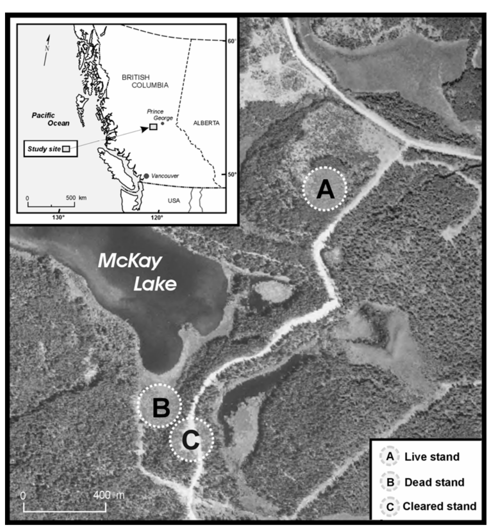

Figure 1. Location of study area and three selected stands.

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

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

MATERIALS AND METHODS

Snow pack characteristics were analyzed bi-weekly in each stand using snowpits. Snow layers were identified within each pit, and the thickness, density, and crystal size/type of each layer was 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 water equivalent (SWE) over the timeframe of the study, as well as the proximity of the snowpack to the 0ºC isotherm. Data were also used to determine meteorologically driven snowpack differences between sites.

Cold content (Q_{cc}) was calculated in each stand for each measurement date, using Equation (1):

$$Q_{cc} = -c_i \cdot \rho_s \cdot z_s \cdot (T_s - T_m) \tag{1}$$

where c_i is the specific heat of ice (2102 J kg^{-1} K^{-1}), ρ_s is the snowpack density, z_s is the snow depth, T_s is the average snow temperature and T_m is the melting point temperature (0ºC). Results were assessed between measurement dates and between stands to determine variations in snowpack condition at the onset of melt.

A previous study used stand-specific meteorological data to examine variations in basic meteorological variables between stands (Boon, 2007).

RESULTS AND DISCUSSION

Bulk snowpack properties

On each measurement date, bulk snow density in the dead stand was less than in all other stands, although it was very close to that of the alive stand (Fig. 2). Snow depth in the dead stand, however, was ~56% of that in the dead stand, but ~168% of that in the alive stand. This resulted in intermediate SWE values that were closer to the alive than the cleared end of the canopy-structure spectrum. Only in the dead stand did snow depth, density and SWE increase incrementally to the onset of melt on 31 March.

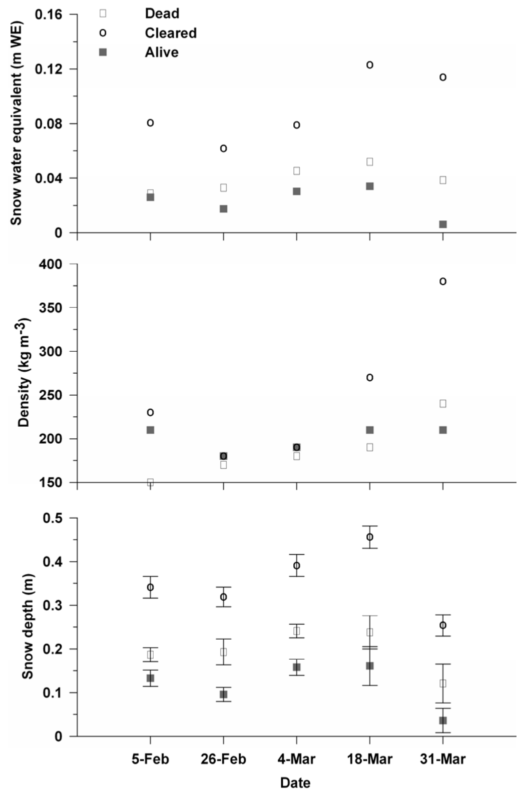

Figure 2. Snow: *(a)* depth (m); *(b)* density (kg m^{-3}); and *(c)* water equivalent (m WE) in each stand on each sampling date. Depth is calculated as the average of eight measurements in the snowpit vicinity; density and SWE are measured in the snowpit.

Cold content in the dead stand was intermediate between high values in the cleared, and lower but closer values in the alive stand (Fig. 3). Only in the dead stand did Q_{cc} steadily increase to maximum SWE on 18 March. Q_{cc} was greatest in the cleared stand, likely due to the fact that both snowpack depth and density, which drive Q_{cc}, were greatest in the cleared stand.

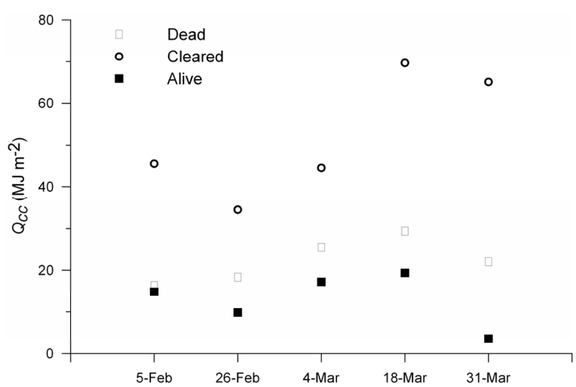

Figure 3. Cold content (Q_{cc}, in MJ m^{-2}) in each stand on each measurement date.

Density

In the dead stand, density in the lower layers increased incrementally while the upper layers maintained a low density. Fresh snowfalls in this stand likely had slower densification rates due to reduced incoming shortwave radiation and wind speeds relative to the cleared stand, and reduced incoming longwave radiation relative to the alive stand (Boon, 2007). In the cleared stand, density in the upper layers of the snowpack increased over the course of the season, while an ice layer at the base of this snowpack remained intact (Fig. 4). Metamorphic processes in the upper snowpack layers were driven by high incoming shortwave radiation and wind speeds (Boon, 2007). The thin snowpack in the alive stand had only one or two distinct layers, and therefore had no density trend.

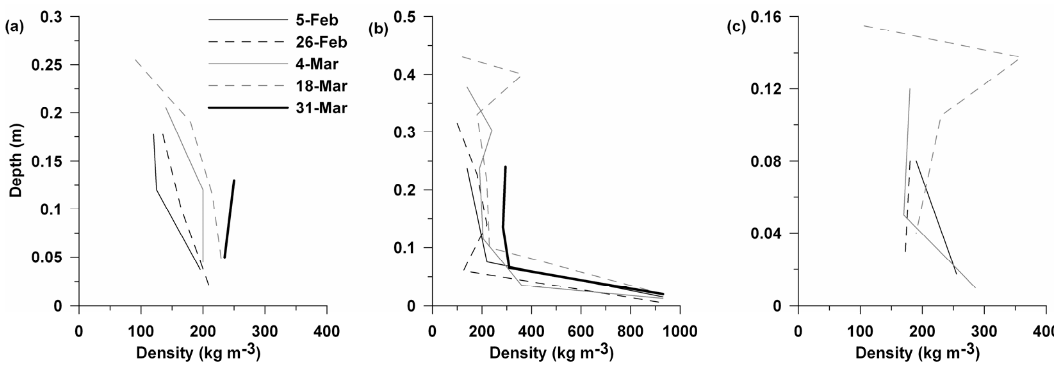

Figure 4. Snow density (kg m^{-3}) profiles in the: *(a)* dead; *(b)* cleared; and *(c)* alive stands on each sampling date.

Temperature

Average snowpack temperature on each sampling date was generally lowest in the dead stand and greatest in the live stand, with the cleared stand in between (Table 2). For the final field measurement, the onset of snowmelt minimized differences between stands. Snow temperature changes between measurement dates were smallest in the dead and alive stands, and greatest in the cleared stand. Comparison of snowpack and air temperature changes between measurement dates indicates that air temperature changes were attenuated in the snowpack (Table 2).

Snow temperature gradients were steepest in the dead stand snowpack throughout the measurement period (Fig. 5). The cleared stand also had a strong temperature gradient, which was mitigated by warming of the upper snowpack layers relative to the dead stand. In the alive stand, a strong temperature gradient did not develop. Temperature gradients in the dead stand become positive after melt onset (31 March), while in the cleared and alive stands they became positive over three weeks earlier, on 4 March (Table 3).

Table 2. Change in air temperature (ΔT_a) and snow temperature (ΔT_s) between measurement dates; average bulk snow temperature (T_s) on each measurement date (all in ºC).

T_s	5 Feb	26 Feb	4 Mar	18 Mar	31 Mar
Dead	-4.6	-8.2	-5.5	-5.0	-0.8
Cleared	-4.5	-7.1	-4.6	-3.0	-0.8
Alive	-2.3	-6.8	-3.1	-3.6	-1.0

ΔT_s	5-26 Feb	26 Feb-4Mar	4-18 Mar	18-31 Mar
Dead	-3.5	3.5	0.8	2.8
Cleared	-2.0	2.3	1.0	1.5
Alive	-3.5	2.8	0.5	2.8

ΔT_a	5-26 Feb	26 Feb-4Mar	4-18 Mar	18-31 Mar
Dead	-5.9	4.6	-0.1	7.7
Cleared	-6.2	5.6	-0.4	7.9
Alive	-6.0	5.2	-0.2	7.4

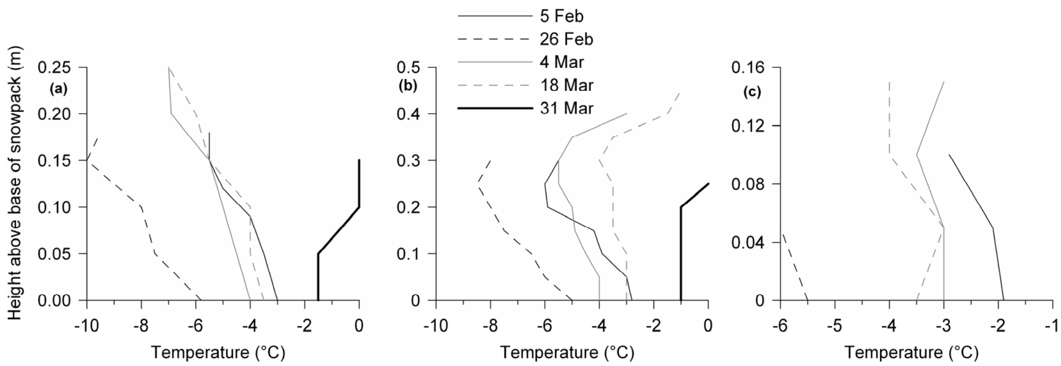

Figure 5. Snow temperature profiles (ºC) for each measurement date in the *(a)* dead; *(b)* cleared; and *(c)* alive stands.

Table 3. Average snowpack temperature gradient (deg/cm) in each stand on each measurement date, based on dial thermometer measurements. Positive = warms to surface; negative = cools to surface.

	5-Feb	26-Feb	4-Mar	18-Mar	31-Mar
Cleared	-0.09	-0.10	0.03	0.04	0.04
Dead	-0.14	-0.21	-0.12	-0.14	0.10
Alive	-0.10	-0.35	0.00	-0.03	0.00

The variation in average snowpack temperature is a function of energy transmission between the atmosphere and the snowpack, while the temperature gradient is largely a function of snow depth and snow surface temperature (Perla and Martinelli, 1976). Snowpack temperature is driven by a complex balance of sensible heat transfer (*H*), incoming shortwave radiation (K_{in}) and incoming longwave radiation emitted from the forest itself (L_{in}) (Price and Petzold, 1984; Boon, 2007). K_{in} warms the snowpack directly, while L_{in} can offset longwave emissions (L_{out}) from the snowpack itself. In the dead stand, *H* was reduced due to the lower air temperature and the lower thermal conductivity of the lower density snowpack. K_{in} was reduced relative to the cleared stand due to the presence of a forest canopy, while L_{in} was reduced relative to the alive stand due to the lower stem density. The resulting decrease in energy available to warm the surface layers created a steeper temperature gradient.

In the cleared stand, *H* flux to the snowpack was augmented by additional energy inputs from K_{in}, which warmed the snowpack. The thermal conductivity of the cleared snowpack was also slightly greater, as it had a greater density. These factors together created a relatively weak temperature gradient in this stand. The low temperature gradient in the alive stand could be due to the higher density and subsequent increased thermal conductivity of the pack. It could also be a function of increased L_{in} from the dense tree cover, which may have offset snowpack cooling driven by low air temperatures.

Crystal structure

The dead stand snowpack had no ice layer development throughout the study period. However, the cleared stand snowpack had a mid-pack ice layer on 4 and 18 March, while the alive stand had a near-surface ice layer on 18 March (Fig. 4). Ice layer formation in the cleared stand was likely caused by melting and refreezing of a fresh snowfall from 26 February due to high K_{in} and an increase in air temperature between 26 February and 4 March (Table 2). In the live stand, however, canopy drip from snowmelt was the main contributor to ice layer development. The lack of melt-freeze layers in the dead stand was a function of reduced K_{in} relative to the cleared stand, and reduced interception relative to the alive stand (Boon, 2007).

A temperature gradient greater than 0.1-0.2 deg/cm and a snowpack temperature less than -6ºC are ideal for the formation of depth hoar, as they develop a strong vapour pressure gradient within the snowpack (Colbeck, 1983). Depth hoar formed in both the dead and cleared stands between 5-26 February, when the snowpack temperature was below -6ºC, but did not develop in the alive stand, as the temperature gradients were too low (Table 4). Changes in depth hoar thickness were least variable in the dead stand, and most variable in the alive and cleared stands.

The variability in depth hoar thickness corresponds with shifts in both the snowpack temperature gradient and average snowpack temperature during the study period. Snowpack temperature increased from 26 February to 4 March, removed some depth hoar from the cleared and alive stands. The relatively constant temperature from 4-18 March (Table 2) then stabilized depth hoar formation. The temperature gradient decreased in all stands, but only in the dead stand was it greater than 0.1deg/cm (Table 3). The continued growth of depth hoar in the alive and cleared stands is likely a result of the semi-impermeable melt-freeze layers, which can alter the vapour pressure gradient and enhance faceted crystal development (Colbeck, 1983).

Table 4. Snow crystal type in each stand on three representative dates.

	5 Feb			4 Mar			31 Mar		
	Open	Dead	Alive	Open	Dead	Alive	Open	Dead	Alive
Surface	/	●	/	/ ⚭	+ /	/	⚭ ○	⚭	○
Mid	□ ●	/	/	□ ●	□ ●	● □	⚭ ○	⚭	○
Base	▬	/	●	∧ ▬	∧ □	□	▭	⚭	○ ▭

In all stands, the mid portion of the snowpack had mixed forms of both faceted (constructive) and rounded (destructive) crystals (Colbeck et al., 1990). Mixed forms develop in response to high variability in both air and snow temperatures. In a warm snowpack (>-6ºC) with a temperature gradient < 0.1ºC/cm, rounded forms will develop relatively quickly, while in a colder snowpack metamorphism is slowed. Over the course of the season, average snowpack temperature changed significantly (Table 2). These temperature shifts, in combination with air temperature changes, caused mixed crystal formation. By 18 March the mixed forms in the alive stand had metamorphosed into a melt-freeze crust with faceted crystals below it. This did not occur in the cleared and dead stands. The removal of mixed forms in the alive stand was caused by canopy drip, which created a melt-freeze crust near the snow surface and subsequently altered the vapour pressure gradient, enhancing faceted crystal growth below.

In addition to crystal layers within the snowpack, several needle layers were observed in the dead stand that did not appear in the open or alive stands. These needles were removed from the dead pine canopy during both wind and snowfall events. They affect snow metamorphism and ablation by absorbing and/or re-radiating heat and longwave radiation. During the snow accumulation period, they can alter crystal growth within the snowpack. During the ablation period, needle layers enhance snow melt due to their lower albedo, as well as their potential to increase longwave re-radiation (Melloh et al., 2001). While the impact of these needle layers was observed to be significant, quantification of this impact is beyond the scope of this study.

CONCLUSION

Snowpack in the dead stand had the lowest density and temperature, and the greatest temperature gradient. It was the only stand with an incremental increase in density, depth and SWE throughout the accumulation season, and the only stand with needle layers within the snowpack. It was also the only stand that formed depth hoar for the duration of the accumulation period, but failed to develop a melt-freeze layer. Cold content was greater than that of the alive stand, but not as high as that in the cleared stand.

Differences between stands were driven by snow depth and stand-specific meteorological conditions, both of which are functions of canopy cover (Boon, 2007). Snow depth and crystal structure in the dead stand were similar to the alive stand early in the season (Fig. 5), but as snow depth increased, crystal structure in the dead stand approached that of the open stand. The dead stand snowpack was thinner relative to the cleared stand due to a reduced canopy cover. The high temperature gradient and depth hoar formation in the dead stand resulted from reduced energy inputs relative to the cleared stand. These reduced energy inputs – in particular incoming shortwave radiation and emitted longwave radiation – also resulted in reduced snowpack densification, minimal warming of surface layers, and no melt-freeze crust formation. The alive stand had a thin snowpack due to a denser canopy cover, but the temperature gradient was minimal due to enhanced longwave emission from the trees that offset snowpack cooling due to air temperature. This stand therefore developed minimal depth hoar, and what did form was driven largely by a canopy-drip induced melt-freeze crust.

It is important to note that this study was completed during a low snow year (65% of normal). In a high snow year, conditions may vary due to altered interactions between the forest canopy and heavier and/or more frequent snowfall events. This could subsequently impact snowpack metamorphism by decreasing the snowpack temperature gradient and increasing snow temperature. There is also the possibility of more heterogeneous stratigraphy, with the formation of additional ice layers due to mid-winter freeze-thaw events that could affect internal metamorphism and result in more complex crystal structures.

Additional research is required to quantify the impact of needle layers on both snow metamorphism and ablation.

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