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The Effects of Mountain Pine Beetle Attack on Snow Accumulation and Ablation: A Synthesis of Ongoing Research in British Columbia

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Introduction

Lodgepole pine (*Pinus contorta* Dougl.) attacked by the mountain pine beetle (MPB) dominates mid-elevation forests throughout the Interior of British Columbia. Depending on tree condition, season and severity of attack, and the weather, trees generally turn from bright red to brown by late summer in the year following attack; in subsequent years, they fade to grey as needles and fine branches are lost (Mitchell and Preisler 1998; Safranyik and Wilson 2006).

Changes in forest canopy through post-infestation needle loss and salvage logging are expected to significantly affect snow accumulation and ablation. Since 2006, research projects have been established in a range of green, red, grey, and clearcut lodgepole pine stands to quantify these effects (Winkler et al. 2005; Winkler and Moore 2006; Beaudry 2007; Boon 2007, 2009a, 2009b; Redding et al. 2007; Dobson 2008; Teti 2009). A detailed description of these ongoing projects can be found in Winkler and Boon (2009). In order to provide timely results for operational forest and water management planning, most research projects include a range of stands in varying condition rather than monitoring the same stands throughout the deterioration period. This research design, in combination with inter-project variations in the choice of unattacked stands, snow survey methods, and the approach to data reporting, complicate interpretation of the results as a coherent whole.

The objective of this article is to provide a concise summary of ongoing post-MPB snow research results and to highlight the range in forest types being surveyed, project designs, snow-sampling techniques, and data summary formats. Key variables and methods for consideration in future project design are suggested to facilitate broader interpretation and application of the results.

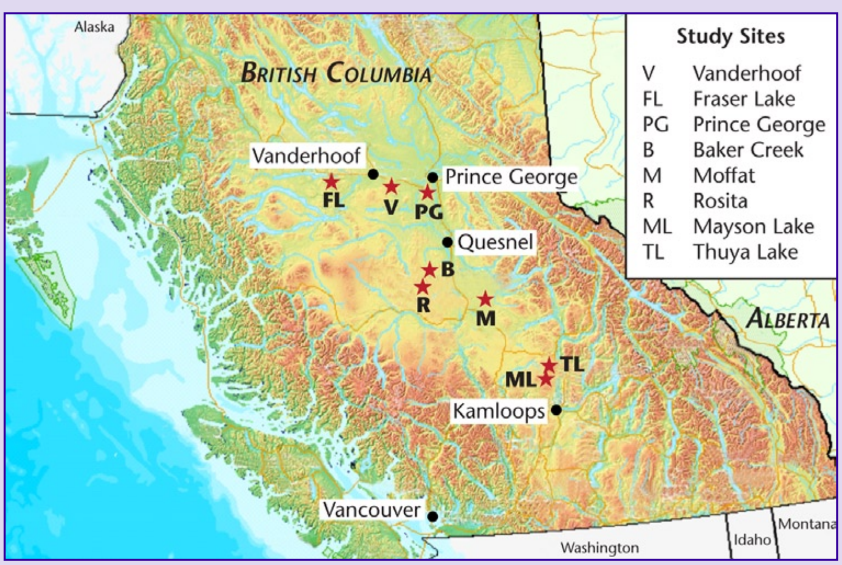

Figure 1. Snow accumulation and ablation research sites in MPB-attacked forests in the British Columbia interior.

Individual Studies

Since 2006, snow data have been collected at eight locations throughout the Interior of British Columbia in areas attacked by MPB (Figure 1). These study sites are located between 730 and 1350 m elevation in the Sub-Boreal Spruce, Sub-Boreal Pine–Spruce, and Montane Spruce biogeoclimatic zones. Forest cover at each site is dominated by lodgepole pine (> 50%). For summary purposes, stands were grouped according to age—intermediate (10–40 years), mature (40–120 years) and old (120+ years)—and categorized as green/red or grey attack. "Green/red attack" includes MPB-attacked stands in which green and red foliage is largely retained. "Grey attack" is defined as stands in which more than 50% of the foliage has been lost and the

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Table 1. Snow accumulation and ablation research sites in MPB-attacked forests in the British Columbia interior. All stands are dominated by lodgepole pine (> 50% of the total stems) and are paired with a clearcut.

Location (Source[a])	BEC subzone[b]	Elevation (m)	Age range	Main canopy height (m)	Stands surveyed	Samples per stand	Survey years
Vanderhoof (3)	SBSmk	835	10–120	15–25	2	44	2006
Vanderhoof (6)	SBSdk	888	10–120+	22	3	36	2008
Fraser Lake (4, 5)	SBSdk	900	40–120+	9–15	3 and 5	36	2007–2008
Prince George: Gregg Creek (1)	SBSdw	835	40–120	22	2	10	2006–2007
Prince George: S1400 Road (1)	SBSdw	760	40–120	23	2	10	2006–2007
Prince George: N1400 Road (1)	SBSdw	730	40–120	26	2	10	2006–2007
Baker Creek (2)	SBSmc	1330	10–120+	9–19	2	[c]	2008
Baker Creek (2)	SBPSdc	920	10–120	11–19	2	[c]	2008
Baker Creek (5)	MSxv	1230	10–120+	10–21	4	36	2008
Moffat (5)	SBPSmk	1134	40–120+	10–25	2	36	2008
Rosita (5)	SBPSxc	1190	10–120+	3–22	3	36	2008
Mayson Lake (6)	MSdm	1290	10–120+	13–23	2	32	2006–2008
Thuya Lake (6)	SBSmm	1350	10–120	20	2	30	2006–2008

[a] Source of information: (1) Beaudry (2007); (2) Bewley (unpublished data, project ongoing); (3) Boon (2007); (4) Boon (2009a, 2009b); (5) Teti (unpublished data, project ongoing); (6) Winkler (unpublished data, project ongoing).
[b] BEC (Biogeoclimatic Ecosystem Classification) subzones: ***www.for.gov.bc.ca/hre/becweb/resources/maps/map_download.html***
[c] SWE obtained by multiplying the mean snow density at 18 sample points by snow depth at 76 sample points.

remaining canopy material is grey. Main canopy tree heights range from 3 to 26 m across the study sites. Clearcut sites were used as a control in all studies. Table 1 summarizes site location, forest cover, and snow survey intensity data for all studies.

Snow surveys varied in duration from 1 to 3 years, in intensity from 10 to 44 sample points per site, and in frequency from weekly to several times over a 2–4 month season. Snow water equivalent (SWE) was generally measured at all sample points in a stand using a standard Federal snow sampler. In some studies, however, snow density was measured at a single location and only snow depth measured at each sample point; the single snow density value was then used to convert depth to SWE for all sample points. Average ablation rates were calculated from the onset of continuous melt to a snowpack depletion date determined by extrapolating ablation beyond the final survey using the ablation rate from the previous sample period.

Results

Table 2 summarizes the results from snow surveys in stands affected by MPB and nearby openings. To reduce the influence of year and geographic location, SWE at the onset of the continuous melt season, average ablation rates, and the date of snowpack depletion are summarized as the percent reduction and difference in the forest relative to the open. Data on which this summary is based are available in the original project reports (see Table 1) and Winkler and Boon (2009).

In the 38 openings surveyed at the onset of melt, SWE ranged from 53 to 258 mm depending on location and year. In the 15 mature

Table 2. Percent reduction in maximum snow water equivalent (MSWE) and average ablation rate (AAR) in the forest relative to the open and the number of days difference in timing of snow disappearance in stands affected by mountain pine beetle in the British Columbia interior, based on data collated in Winkler and Boon (2009).

Forest age class (years)	Attack class	Reduction in MSWE (%)			Reduction AAR (%)			Difference (days) in snow depletion date (Forest – Open)	
		No. sites	Average	Range	No. sites	Average	Range	Average	Range
Old (120+)	Green/red	3	22	31 to 6	2	39	42 to 36	7	4 to 10
Mature (40–120)	Green/red	12	26	57 to +9	3	38	48 to 27	2	0 to 3
Intermediate (10–40)	Green/red	12	16	72 to +7	5	22	49 to +7	2	–5 to 9
Old (120+)	Grey	7	11	21 to +9	2	22	29 to 14	9	–1 to 3
Mature (40–120)	Grey	9	16	58 to +28	3	37	57 to 25	3	0 to 6
Intermediate (10–40)	Grey	1	21		1	38		12	12

and older green/red stands, SWE averaged 25% less than in the open, ranging from 57% less to 9% more depending on the location and year. In 16 mature and older grey stands, SWE averaged 13% less than in the open, ranging from 58% less to 28% more. Differences in SWE between the 12 intermediate green/red stands and the open showed even more variability, ranging from 72% less to 7% more, with an average of 16% less. This broad range of results reflects differences in stand structure within this age category. Only one intermediate grey stand was surveyed, in which SWE was 21% less than in the open.

In 16 openings, average snow ablation rates ranged from 4.8 to 13.7 mm per day, depending on location and year. In the mature/old green/red stands, ablation rates were on average 38% less than in the open, ranging from 27% to 48% slower. Similar reductions were observed in the mature/old grey stands, where ablation rates were on average 31% slower relative to the open with a range of 14–57%. In the intermediate green/red stands, ablation rates were on average 22% slower than in the open, ranging from 49% slower to 7% faster.

The snowpack was retained for an average of 2–12 days longer in the forest than in the open across all age and attack classes. The large variability in depletion dates again highlights the dependence of snowpack processes on hydrometeorological conditions and stand structure at any given location.

Issues in Comparing Study Results

Developing generally applicable forest practice guidelines by broadly extrapolating results from multiple studies requires a clear understanding of study design, location, environmental conditions, vegetation, survey methods, and approaches to data analysis at each study site. Although confidence in this approach is increased when similar results are obtained at several locations, identification of similarities is complicated by minimal or inconsistent descriptions of study conditions and approaches, and differences in project objectives and forest cover types of interest in each study.

The eight post-MPB snow research projects discussed here applied a variety of site selection criteria, stand descriptors, snow survey methods, and data summary formats. These variations in approach complicate synthesis of the results, particularly inconsistencies related to:

- substitution of green mixed-species stands for pine stands, burned stands for grey stands, and space for time;
- descriptions of stand composition and structure, including the level of attack and the definition of green/red/grey;
- differences in snow survey frequency, intensity, and duration; and
- analysis of snow variables of interest, such as average versus maximum weekly ablation rates.

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Site Selection Criteria

The greatest difficulty when designing research projects to quantify the effects of MPB on snow accumulation and ablation is in finding an opening with neighbouring stands that represent all categories of attack in proximity to a healthy green stand of similar species and structure. Researchers have attempted to overcome this issue by substituting green mixed species and burned stands for healthy green pine and grey stands, respectively. However, differences in snow accumulation and ablation between green and open stands depend on stand composition, with generally smaller differences between open and pine stands than between open and mixed (Engelmann spruce, subalpine fir, pine) stands (e.g., Pomeroy and Goodison 1997; Winkler and Roach 2005). Additionally, differences in canopy structure (including vertical distribution of crowns, density, and condition), stem density, and possibly albedo between grey and burned stands likely result in differing effects on snow processes.

Studies have also commonly substituted space for time in an attempt to obtain results for each level of attack over a few years, rather than track changes in the same stands over 5 or more years as they turn from green to grey. The main difficulty with this approach is the potential for high spatial variability in snow accumulation and melt over short distances, which will confound results observed between adjacent forest and open sites. For example, at Mayson Lake (Figure 1), the difference in April 1st SWE between two clearcut openings located 2 km apart on flat terrain was –43 mm and +18 mm in 2007 and 2008, respectively, while differences between the forest and open in the same years were –61 mm and –56 mm.

Stand Description

Although it is well understood that forests have a significant effect on snow processes, detailed stand descriptions are often unavailable. Generally, tree species are named but the percentage of each in a stand is not quantified. For multi-layered stands, descriptions of the main canopy, intermediate layers, and understorey are not commonly provided. Also not uniformly quantified is stand condition, including growth relative to age and site productivity and the number and species of trees attacked by insects or disease, damaged by fire, wind, or snow, or that are dead. Definitions of red and grey attack classes differ among studies (Figure 2) and variously include metrics related to the proportion of red needles in individual tree crowns, the magnitude of needle loss, and the number of red versus grey trees within a stand.

Snow Survey Methods

Snow surveys are time consuming and costly, and therefore efficiencies in measurement methods and survey design are commonly considered. To increase survey efficiency, SWE can be determined by multiplying snow depth at all sample points in the stand of interest by a single or few snow density measurements. However, values obtained by this method likely differ from the average of SWE measured at all points, thus affecting comparisons between stands and studies. For example, in a clearcut at Mayson Lake in mid-April 2008, SWE measured at 32 sample points was 186 mm, whereas SWEs calculated from 32 depth measurements and the maximum and minimum snow densities on that date were 219 and 153 mm, respectively. Using SWE measured at all sample points, the mature forest had 46% lower SWE than the clearcut, compared with 32% based on depth measurements and maximum density in both stands, and 67% based on depth measurement and minimum density in both stands.

Snow surveys also vary in intensity, frequency, and duration. Surveys discussed in this summary variously include 10–44 samples per forest type and opening, range in frequency from weekly to only twice over a season of up to 4 months, and are continued over a period of 1–3 years. Differences in sampling intensity affect the differences in absolute SWE values between sites, while differences in sampling frequency potentially affect recorded SWE at the onset of melt and will affect calculations of both the average ablation rate and date of snowpack

Figure 2. Examples of stands with red pine: (a) all red; (b) mixed green and red; and (c) red and grey in the main canopy and green in the understorey (BC Ministry of Forests and Range photos).

removal. Single or few year duration surveys may not represent a complete range of weather conditions, which can also affect results.

Data Analysis

The variables of interest most commonly described in snow studies include maximum SWE, SWE at the onset of the melt season, average ablation rate, and date of snowpack depletion. Since manual snow surveys are not undertaken daily, the values used for these variables will depend somewhat on the study. For example, maximum SWE or SWE at the onset of the continuous melt period is often taken as SWE on April 1st. Although the actual maximum may precede or follow this date, the recorded maximum is ultimately a function of snow survey dates relative to the actual maximum date (Table 3). Ablation rate is influenced by the period over which it is calculated. For example, in the open at Mayson Lake the average melt rate for the 2007 winter was 6.6 mm per day, whereas the maximum ablation rate over a single week (the minimum sampling frequency) was 13.8 mm per day (Table 3). Describing ablation as a ratio of that in the forest to the open reduces differences between average and the maximum weekly ablation rates (as shown in Table 3). Date of snowpack depletion may be taken as the first survey date on which no snow remained or may be calculated based on the ablation rate during the survey preceding the observed zero SWE date.

Table 3. Date of maximum SWE versus 1 April SWE, and average and maximum weekly ablation rates in a clearcut, young pine, and mature mixed-species stand at Mayson Lake, BC (F:O is the ratio of forest to open ablation rate). Reproduced from Winkler and Boon (2009).

Forest cover	Year	April 1 minus date of MSWE	Ablation rate (mm per day)	
			Average (F:O)	Maximum weekly (F:O)
Clearcut	2007	–15	6.6	13.8
	2008	0	7.6	16.2
Young red pine	2007	–20	5.8 (0.88)	11.6 (0.84)
	2008	2	5.6 (0.74)	12.0 (0.74)
Mature green mixed	2007	–18	4.2 (0.64)	10.2 (0.74)
	2008	–7	4.4 (0.58)	9.7 (0.60)

Key Considerations for Studies of Forest–Snow Interactions

This synthesis of results from eight snow research projects in British Columbia clearly highlights the importance of study design, clarity of site description, and consistency in data analyses between studies. When study results from many sites will be pooled to provide operational interpretations, clearly defined site-selection criteria should be developed, which will be applied by all researchers before project establishment in the field. Study design influences the ability to detect hydrologically significant differences in SWE. Survey methods and sample sizes should be sufficient to achieve the required accuracy and to overcome within-stand variability, while also capturing between-stand variability without overtaxing the surveyors. The timing of measurements should also be considered relative to the snow variable(s) of interest.

Site selection is the most important step in the establishment of snow research projects. Forested and open areas should be located close together. When stands are not adjacent, differences in the snow variables of interest between the stands farthest apart should be quantified to ensure that differences in snow are related to forest cover rather than topography. When study stands are meant to approximate actual stands of interest (e.g., green mixed species for green pine stand; burned for grey-attack stand), differences in attributes between the study stand and the stand type of interest should be quantified, and the stem and canopy attributes of the study stand should be as similar as possible to those that would occur in the stand of interest.

Both the synthesis of results and the confidence in extrapolating these results will be improved through clear descriptions of forest cover, particularly those variables that are most highly correlated with SWE and ablation (e.g., Pomeroy and Goodison 1997; Teti 2003; Winkler and Roach 2005; Talbot et al. 2006):

- leaf area
- canopy gap fraction
- canopy density
- basal area

In addition to these variables, basic forest cover descriptors required when collating and extrapolating research results include:

- stand structure (single or multi-layered with clumped or evenly distributed stems);

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- stem density;
- tree species in each layer (main canopy vs. the understorey);
- proportion of each species in all layers;
- tree height by layer; and
- tree condition in each layer by species.

Leaf area, gap fraction, and canopy density can be estimated from hemispherical photography (Fournier et al. 1996). When using this technique, the sky conditions under which photographs are collected should be noted, and photo analysis should follow standardized procedures using common software (e.g., Frazer et al. 1999).

All other stand variables should be described using standard forest inventory and health procedures (e.g., ***www.for.gov.bc.ca/hts/vri/standards/index.html***; ***www.for.gov.bc.ca/TASB/LEGSREGS/FPC/FPCGUIDE/health/Httoc.htm***). Any modifications to inventory procedures or definitions should be clearly documented. When non-standard variables are used, an adequate number of standard descriptors should also be provided to allow for broader application of results.

In MPB-attacked stands, green attack is operationally defined as the period when tree crowns remain green, pitch tubes are visible on the bole, and beetle brood is still in the tree. Red attack is the period when foliage turns bright red and then fades to dull red, usually the summer following attack when beetles have completed their development and emerged from the trees. Finally, grey attack is the stage at which needles are grey or absent, tree bark loosens and falls, and no beetles remain in the trees, generally 2 or more years after attack (L. Maclauchlan, BC Ministry of Forests and Range, pers. comm., October 2009). Annual aerial surveys using Provincial Aerial Overview Survey protocols (***www.for.gov.bc.ca/hfp/health/overview/methods.htm***) provide a spatial classification of bark beetle attack severity. Severity ratings range from trace to very severe defined by the level of mortality within a mapped polygon (< 1% to +50% of the trees are red, respectively). Ratings provided through the provincial overview surveys would most clearly and consistently communicate research stand condition, facilitating multi-study comparisons and operational interpretation of results.

Snow surveys must be designed to capture interstand variability in hydrologically relevant variables (e.g., SWE) at a relatively high level of accuracy. To allow for study intercomparison, snow survey design and sampling technique should follow standard methods for measuring SWE, ablation, and snow distribution (e.g., Beaumont and Work 1963; Goodison et al. 1981; Spittlehouse and Winkler 1996; Lundberg and Halldin 2001; Weiler et al. 2008 Boon et al. 2009). Snow variables and calculation methods should also be clearly defined. For example, ablation rates vary depending on the calculation method used, and particularly on the dates chosen to represent the length of snowmelt season (e.g., Table 3).

When presenting research results, actual values and variances should be shown along with standardized variables, such as the percent reduction in, difference between, or ratio of snow in forest to open sites. Providing the mean and range of values enables others to collate results from multiple studies to answer other questions of interest.

In cases where studies vary widely in their objectives and availability of resources, care should be taken in collating the results to ensure that they represent similar forest cover conditions and that differences are actually a result of forest cover and environment, rather than of study design and/or data analysis techniques.

Summary

Snow surveys across the Interior of British Columbia show a wide range of changes in snow accumulation and ablation following mountain pine beetle infestation. Although a portion of these differences can be attributed to both the spatial variability in snow accumulation and melt and the effects of changing forest cover, some can also be attributed to the research methods applied. The development and utility of forest and water management guidelines based on multiple research projects depends, in part, on the careful description of forest and other environmental attributes at each study site. Additionally, the use of standardized snow survey design and sampling techniques will improve our ability to conduct future multi-study syntheses.

The use of standardized snow survey design and sampling techniques will improve our ability to conduct future multi-study syntheses.

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