A SUMMARY OF RESEARCH INTO THE EFFECTS OF MOUNTAIN PINE BEETLE RELATED STAND MORTALITY ON SNOW ACCUMULATION AND ABLATION IN BRITISH COLUMBIA, CANADA

Rita Winkler[1] and Sarah Boon[2]

ABSTRACT

Extensive mountain pine beetle related forest mortality throughout the Interior of British Columbia raises concern regarding the effects of stand deterioration on snow accumulation and ablation, and spring runoff. Studies quantifying post-pine beetle snow accumulation and ablation rates show that, on average, once 50% or more of the canopy in mature stands has been lost (defined here as grey attack), snow accumulation is only 13% lower than that in the open compared to a 25% reduction in mature green/red attack. Reductions in snow ablation rate were similar, on average, in the green/red and grey attack: 38% and 31%, respectively. The average snow duration in both attack classes is also similar (3-4 d longer than in the open). Differences in snow accumulation and melt are highly variable between study locations and years, with spatial differences often exceeding those related to stand condition. Development of best management practice guidance for broad geographic areas is dependent upon coordinated research efforts at the same scale, as well as consistency in project design, stand description, survey and data analysis methods. (Keywords: pine beetle, forest mortality, snowpack reduction)

INTRODUCTION

Lodgepole pine *(Pinus contorta* Dougl.*)* dominates mid-elevation forests throughout the interior of British Columbia (BC), much of which has been attacked by mountain pine beetle (MPB). By late summer in the year following MPB attack, trees turn from bright red to brown; in subsequent years they fade to grey as needles and fine branches are lost (Mitchell and Preisler 1998). The trajectory of tree mortality is dependent on a variety of factors, including the season of attack, the attack density, tree age and vigor, and the weather (hot/dry conditions during late summer and early fall may advance the rate at which crowns fade) (Safranyik and Wilson 2006).

Changes in forest canopy through post-infestation needle loss and MPB management approaches, such as salvage logging, are expected to significantly affect snow accumulation and ablation, with potential downslope and downstream consequences. Previous studies in lodgepole pine-dominated stands have shown 5 – 70% higher snow water equivalent (SWE) at the onset of the melt season and ablation rates 30 - >100% higher in clearcuts than in the forest, depending on winter precipitation, the weather during the melt season, and forest cover (Toews and Gluns 1986; Metcalfe and Buttle 1998; Pomeroy et al. 2002; Winkler et al. 2005: Winkler and Moore 2006). A post-wildfire study found that a 90% reduction in lodgepole pine canopy cover increased snow ablation rates by 57% to equal those in a clearcut (Skidmore et al. 1994).

Since 2006, research projects have been established in a range of green-, red-, and grey-attack lodgepole pine stands in BC to quantify post-MPB changes in snow accumulation and ablation (Winkler et al. 2005; Winkler and Moore 2006; Beaudry 2007; Redding et al. 2007; Boon 2007, 2009a, 2009b; Dobson 2008; Teti 2009; Bewley unpub. data). Given the rate of forest change following infestation and salvage logging, as well as the pressure to obtain field data to guide operational forest and water management decisions, research has been time-limited and requests for interpretation of early results ongoing. Thus, most commonly a range of stands in varying condition have been studied rather than sampling the same stand throughout the deterioration period. In most studies, the attacked stands are lodgepole pine while the corresponding healthy (control) stands contain a mix of pine, Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt). Snow surveys from each study provide two or more years of snow accumulation and ablation data, with sampling frequencies varying from weekly to only one or two per season. Some studies focus on maximum SWE and maximum weekly ablation rate, while others use April 1 SWE and average ablation rate.

Paper presented Western Snow Conference 2009

[1] Rita Winkler, BC Ministry of Forests and Range, 515 Columbia Street, Kamloops, BC, V2C 2T7, rita.winkler@gov.bc.ca

[2] Sarah Boon, University of Lethbridge, sarah.boon@uleth.ca

The objective of this project was to compile these research results to provide estimates of changes in potential stand-scale snowmelt runoff for forest planners and water managers. Comparison of results has highlighted inconsistencies in project design, stand selection, sampling methods, stand description, and data analysis which complicate the interpretation of the results. This paper summarises the results of snow studies throughout the Interior of BC, and outlines inconsistencies between studies that must be considered when interpreting summary results and designing future projects.

STUDY AREAS AND DATASETS

Data were collated from snow surveys completed between 2006 and 2008 at eight locations throughout the interior of BC (Figure 1), from 51 to 54ºN. The study sites are located in the Sub-boreal Spruce, Sub-boreal Pine/Spruce, and Montane Spruce biogeoclimatic zones, from 730 to 1350 m a.s.l. Each site includes several forest stands in which forest cover is dominated by lodgepole pine (>50%), with lesser proportions of Engelmann spruce and subalpine fir. Trees in each stand range in age from 10 to >120 years, and were categorized into intermediate (10-40 y), mature (40-120 y) and old (120+ y) age classes. Main canopy height ranged from 3 to 26 m and attack classes included green, red and grey. In this summary, green/red attack includes those stands that have been attacked by MPB where the foliage is largely retained and is green or red in colour. Grey attack is defined as stands where >50% of the foliage has been lost and the remaining canopy material is grey. Clearcut or open sites were used as a control in all studies. Basic characteristics of each study site are summarized in Table 1.

SWE has been measured at each of these sites for one to three years, with 10 to 44 measurement points per site. Measurement frequencies ranged from once or twice per season to weekly. SWE was usually measured with a standard Federal snow tube. In some studies only snow depth was measured at each survey point, and average density measured at a single location was used to convert depth to SWE for all 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.

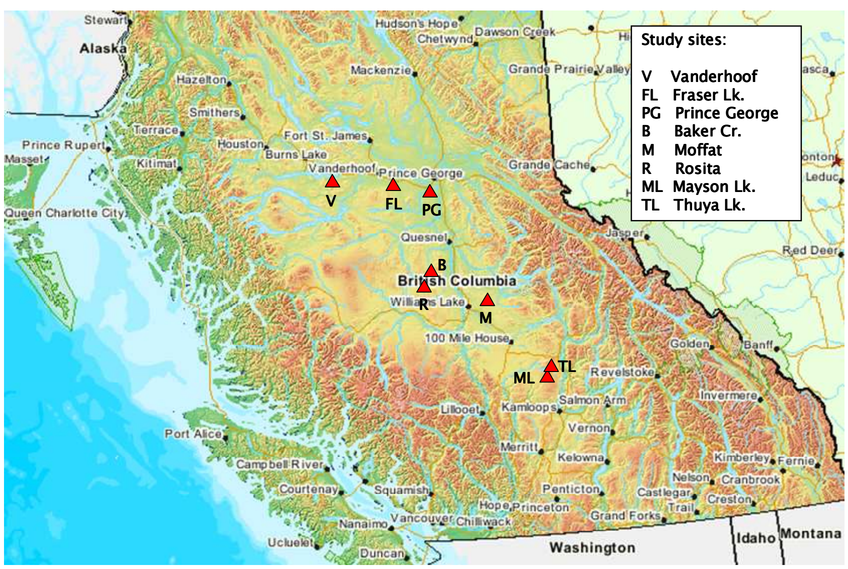

Figure 1. Locations of post mountain pine beetle snow study sites in Interior British Columbia.

Table 1. Location and study information for sites throughout the Interior of BC where snow accumulation and ablation post-mountain pine beetle attack are being surveyed (see key below).

Location (Source)	BEC Subzone	Avg. Elev. (m)	Species (%)	Age Class (years)			Ht (m)	Samples in each stand	Survey Year	Attack Class	
				120+	40-120	10-40				Green/Red	Grey
Vanderhoof(3)	SBSmk	835	Pl(70)S(20)		√		25	44	2006		√
Vanderhoof(3)	SBSmk	835	Pl(100)			√	15	44	2006	√	
Vanderhoof (6)	SBSdk	888	Pl(100)	√			22	36	2008		√
Vanderhoof (6)	SBSdk	888	Pl(100)		√		10	36	2008	√	
Vanderhoof (6)	SBSdk	888	Pl(100)			√	5	36	2008	√	
Fraser Lk.(4)	SBSdk	900	Pl(83)S(17)	√			15	36	2007		√
Fraser Lk.(4)	SBSdk	900	Pl(83)S(17)	√			15	36	2008		√
Fraser Lk.(4)	SBSdk	900	Pl(97)S(3)		√		9	36	2007	√	
Fraser Lk.(4)	SBSdk	900	Pl(97)S(3)		√		9	36	2008	√	
Gregg Cr.(1)	SBSdw	835	Pl(94+)		√		22	10	2006	√	
Gregg Cr.(1)	SBSdw	835	Pl(94+)		√		22	10	2007		√
S1400 Rd.(1)	SBSdw	760	Pl(63)S*(37)		√		23	10	2006		√
S1400 Rd.(1)	SBSdw	760	Pl(63)S*(37)		√		23	10	2007		√
N1400 Rd.(1)	SBSdw	730	Pl(100)		√		26	10	2006	√	
N1400 Rd.(1)	SBSdw	730	Pl(100)		√		26	10	2007		√
Baker Cr.(2)	SBSmc	1330	Pl(69)S(31)	√			19	*	2008		√
Baker Cr.(2)	SBSmc	1330	Pl(88) S(12)			√	9	*	2008	√	
Baker Cr.(2)	SBPSdc	920	Pl(96) S(4)		√		19	*	2008		√
Baker Cr.(2)	SBPSdc	920	Pl(93) S(7)			√	11	*	2008	√	
Baker Cr.(5)	MSxv	1237	Pl(90&95)S(10&5)	√			21	36	2008		√
Baker Cr.(5)	MSxv	1224	Pl(95)S(5)		√		16	36	2008	√	
Baker Cr.(5)	MSxv	1224	Pl(100)		√		16	36	2008		√
Baker Cr.(5)	MSxv	1224	Pl(100)			√	10	36	2008	√	
Moffat (5)	SBPSmk	1134	Pl(100)	√			25	36	2008		√
Moffat (5)	SBPSmk	1134	Pl(100)		√		10	36	2008	√	
Rosita (5)	SBPSxc	1190	Pl(100)	√			22	36	2008		√
Rosita (5)	SBPSxc	1190	Pl(100)		√		7	36	2008	√	
Rosita (5)	SBPSxc	1190	Pl(100)			√	3	36	2008	√	
Mayson Lk.(6)	MSdm	1290	Pl(56)S(28)Bl(16)	√			23	32	2007	√	
Mayson Lk.(6)	MSdm	1290	Pl(56)S(28)Bl(16)	√			23	32	2008	√	
Mayson Lk.(6)	MSdm	1290	Pl(99)			√	13	32	2007	√	
Mayson Lk.(6)	MSdm	1290	Pl(99)			√	13	32	2008	√	
Thuya Lk.(6)	SBSmm	1350	Pl(77)S(17)		√		20	30	2006	√	
Thuya Lk.(6)	SBSmm	1350	Pl(77)S(17)		√		20	30	2007		√
Thuya Lk.(6)	SBSmm	1350	Pl(77)S(17)		√		20	30	2008		√
Thuya Lk.(6)	SBSmm	1350	Pl(94)			√	10	30	2006	√	
Thuya Lk.(6)	SBSmm	1350	Pl(94)			√	10	30	2007	√	
Thuya Lk.(6)	SBSmm	1350	Pl(94)			√	10	30	2008	√	

Key to abbreviations and symbols used in Tables 1 and 2:

Source of information:

1	Beaudry (2007)
2	Bewley (unpublished data)
3	Boon (2007)
4	Boon (2009)
5	Teti (unpublished data)
6	Winkler (unpublished data)

Site and study descriptors:

BEC (Biogeoclimatic Ecosystem Classification) subzones:

MSdm	Montane spruce dry, mild
MSxv	Montane spruce very dry, very cold
SBSdw	Sub-boreal spruce dry, warm
SBSdk	Sub-boreal spruce dry, cool
SBSmc	Sub-boreal spruce moist, cold
SBSmk	Sub-boreal spruce moist, cool
SBSmm	Sub-boreal spruce moist, mild
SBPSdc	Sub-boreal pine spruce dry, cold
SBPSmk	Sub-boreal pine spruce moist, cool
SBPSxc	Sub-boreal pine spruce very dry, cold

Species forming the main canopy (comprising >10% of the total stems) (%):

Bl	subalpine fir
Pl	lodgepole pine
S	Engelmann or hybrid spruce
S*	black spruce

Ht average dominant plus codominant (main canopy) tree height

Samples in each stand:

* SWE obtained by multiplying the mean snow density at 18 sample points by snow depth at 76 sample points

Level of attack:

Green/Red: ≥ 50% of the dominant and codominant trees are not attacked or are at the green to red attack stage and retain needles

Grey: ≥ 50% of the dominant and codominant trees are grey or are snags and have lost more than 50% of their needles

RESULTS

The results of snow surveys in lodgepole pine-dominated stands affected by MPB are summarized in Table 2. These surveys quantified SWE at the onset of the continuous melt season, average ablation rates, and the day on which the snowpack was depleted in 2006 to 2008. Results are summarized as ratios of forest to open (F:O) to reduce the influence of year and geographic location (Table 3).

SWE at the onset of melt in the 38 openings surveyed varied from 53 to 258 mm depending on location and year. In the 15 mature and older green/red stands, SWE averaged 25% less than in the open, varying 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, varying from 58% less to 28% more. Differences in SWE between the 12 intermediate green/red stands and the open were even more variable, ranging from 72% less to 7% more, with the average being 16% less. This broad range of results reflects the significant 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.

Average snow ablation rates over the melt season were measured at 16 forested sites, five of which were mature or old green/red, five mature or old grey, five intermediate green/red and one intermediate grey attack. The range of ablation rates for all groups of stands overlapped. In the open, ablation rates varied from 4.8 to 13.7 mm d^{-1}, depending on location and year. The reduction in ablation rate in mature/old grey stands relative to the open was 31% on average with a range of 14 to 57% less. The average reduction in ablation rate in the mature/old green/red stands was similar to that in the mature/old grey stands: 38% less on average and a range of 27 to 58%. In the intermediate green/red stands, ablation rates were on average 22% slower than in the open, ranging from 49% slower to 7% faster.

Across all forest ages and attack classes, the snowpack was depleted five days earlier to 12 days later at the forested sites than in the open, again depending on location, year, stand age, and level of attack. These results highlight the dependence of snowpack processes on hydrometeorological conditions and stand structure at any given location.

Table 2. Snow water equivalent (SWE) at the onset of melt, average ablation rates (AAR), and the day of year by which the snowpack was depleted, as well as the ratios of forest to open (F:O) and days different from the open (DD), in pine-leading stands that have been affected by mountain pine beetle in the Interior of BC. Stands are grouped by age class and are ordered from north to south (see key above for Table 1).

Location (Source)	Survey Year	Survey Day	SWE (mm) (F:O) Open	SWE Green/Red Attack	SWE Grey Attack	AAR (mm d^{-1}) (F:O) Open	AAR Green/Red Attack	AAR Grey Attack	Day snow depleted (DD) Open	DD Green/Red Attack	DD Grey Attack
Old (120+ years) stands											
Fraser Lk.(4)	2007	63	258		227 (0.88)	10.9		9.4 (0.86)	119		118 (-1)
Fraser Lk.(4)	2008	92	154		146 (0.95)	13.7		9.7 (0.71)	124		127 (+3)
Baker Cr.(2)	2008	88	245		193 (0.79)						
Baker Cr.(5)	2008	109	156		123 (0.79)						
Vanderhoof(5)	2008	109	158	149 (0.94)	150 (0.95)						
Moffat(5)	2008	109	136		149 (1.09)						
Rosita(5)	2008	109	117		96 (0.82)						
Mayson Lk.(6)	2007	92	198	137 (0.69)		6.6	4.2 (0.64)		118	128 (+10)	
Mayson Lk.(6)	2008	91	196	140 (0.71)		7.6	4.4 (0.58)		131	135 (+4)	
Mature (40–120 years) stands											
Vanderhoof(3)	2006	77	123		52 (0.42)	4.9		2.1 (0.43)	96		98 (+2)
Fraser Lk.(4)	2007	63	258	282 (1.09)		10.9	8.0 (0.73)		119	122 (+3)	
Fraser Lk.(4)	2008	92	154	123 (0.80)		13.7	8.5 (0.62)		124	127 (+3)	
Gregg Cr.(1)	2006	65	124	74 (0.60)							
Gregg Cr.(1)	2007	58	226	171 (0.76)	183 (0.81)						
S1400 Rd.(1)	2006	65	97	42 (0.43)	71 (0.73)						
S1400 Rd.(1)	2007	58	168	90 (0.53)	134 (0.80)						
N1400 Rd.(1)	2006	65	53	53 (1.0)							
N1400 Rd.(1)	2007	58	105	78 (0.74)	134 (1.28)						
Baker Cr.(2)	2008	88	107		100 (0.93)	4.8		3.6 (0.75)	110		116 (+6)
Baker Cr. (5)	2008	109	156	117 (0.75)							
Baker Cr. (5)	2008	109	126		131 (1.04)						
Vanderhoof(5)	2008	109	158	123 (0.78)							
Rosita(5)	2008	109	117	85 (0.73)							
Thuya Lk.(6)	2006	94	180	131 (0.73)		8.7	4.5 (0.52)		112	112 (0)	
Thuya Lk.(6)	2007	89	176		141 (0.80)	5.9		4.2 (0.71)	109		109 (0)
Thuya Lk.(6)	2008	88	216		169 (0.78)						
Intermediate (10–40 years) stands											
Vanderhoof(3)	2006	77	123	34 (0.28)		4.9	2.5 (0.51)		96	91 (-5)	
Baker Cr.(2)	2008	88	107	104 (0.97)							
Baker Cr.(2)	2008	88	245	223 (0.91)	193(0.79)	4.8		3.0 (0.62)	110		122 (+12)
Baker Cr.(5)	2008	109	126	135 (1.07)							
Vanderhoof(5)	2008	109	158	137 (0.87)							
Moffat(5)	2008	109	154	118 (0.77)							
Rosita(5)	2008	109	117	100 (0.85)							
Mayson Lk.(6)	2007	92	198	184 (0.93)		6.6	5.8 (0.89)		118	127 (+9)	
Mayson Lk.(6)	2008	91	196	155 (0.79)		7.6	5.6 (0.74)		131	134 (+3)	
Thuya Lk.(6)	2006	94	180	158 (0.88)		8.7	6.1 (0.70)		112	116 (+4)	
Thuya Lk.(6)	2007	89	176	165 (0.94)		5.9	6.3 (1.07)		109	109 (0)	
Thuya Lk.(6)	2008	88	216	179 (0.83)							

Table 3. Ratios of maximum snow water equivalent (SWE) and average ablation rate in the forest relative to that in the open (F:O) and the number of days difference in timing of snow disappearance (F-O) in stands affected by mountain pine beetle in the Interior of BC.

	F:O Maximum SWE		F:O Average Ablation Rate		Difference in Snow Depletion Date (F-O)	
	Green/Red Attack	Grey Attack	Green/Red Attack	Grey Attack	Green/Red Attack	Grey Attack
Old stands (120+ years)						
Average	0.78	0.89	0.61	0.78	7	1
Range	0.69 - 0.94	0.79 - 1.09	0.58 - 0.64	0.71 - 0.86	4 - 10	-1 - 3
# Sites	3	7	2	2	2	2
Mature stands (40 - 120 years)						
Average	0.74	0.84	0.62	0.63	2	3
Range	0.43 - 1.09	0.42 - 1.28	0.52 - 0.73	0.43 – 0.75	0 – 3	0 – 6
# Sites	12	9	3	3	3	3
Intermediate stands (10–40 years)						
Average	0.84		0.78		2	
Range	0.28 - 1.07	0.79	0.51 - 1.07	0.62	-5 to 9	12
# Sites	12	1	5	1	5	1

ISSUES IN COMPARING STUDY RESULTS

While compiling the results of the eight research projects, inconsistencies were noted in regards to project design, stand description, snow survey methods, and data analysis, making it difficult to develop comprehensive management interpretations applicable throughout Interior BC.

Project design

The greatest difficulty in designing a research project to quantify MPB effects on snow accumulation and melt is in finding an opening with neighboring stands representing all categories of attack, as well as a healthy green stand of similar species mix and stand attributes. In the central interior, where large areas of lodgepole pine are grey, it is nearly impossible to find a stand-scale patch of healthy green pine trees of the same height, stem density and distribution, and canopy characteristics. Consequently, researchers have selected green stands that are not pure pine but of mixed species. This is problematic as previous research has clearly shown that differences between mature green pine and open areas are often smaller than those observed between mixed Engelmann spruce, subalpine fir and pine and open areas (eg. Winkler 2001). In other areas of the province, where most pine is at the red attack stage, grey stands do not exist adjacent to the other stand types of interest; thus in some cases burned stands are used as a surrogate. This is likely not a viable assumption, as forest structure in grey stands differs from that in burned stands in terms of canopy and stem density, with differing impacts on snow processes.

At sites where snow surveys were underway while stands were healthy, it will take approximately five years from the onset of MPB attack for most of the canopy material to be lost. In these areas, some researchers have substituted space for time: studying several stands over a relatively small area that represent stages of MPB infestation. This approach can also be problematic due to the large spatial variability in snow accumulation and melt even over short distances. For example, at Mayson Lake in southern BC (Figure 1), the difference in April 1st SWE between two clearcut openings located 2 km apart on flat terrain was -43 mm in 2007 and +18 mm in 2008. These differences will confound those observed between adjacent forest and open sites, which at the same site vary from 50 to 60 mm.

In another study not included in this summary, the location of the open area was identified as inappropriate after one year of measurements, as it was located in a gully that accumulated an excess of snow relative to more level terrain. An alternate open site was used in the second year; however, both years' results were reported and differences between locations not elaborated upon.

Stand description

Study stand descriptions vary considerably among projects. In general, tree species are named but the percentage of each in total stand composition is not quantified. For multi-layered stands, descriptions of the main canopy, intermediate layers, and understorey are not commonly provided. Additionally, definitions of red and grey attack classes vary among studies, including the proportion of red needles, needle loss in individual tree crowns, and the number of red and grey trees required within a stand to be classified as red or grey. In this summary, only stands with >50% pine in the main canopy are included; trees described in the project summaries as retaining ≥50% of their needles are classified as green/red and those with grey canopies retaining <50% of their needles are classified as grey.

Snow survey methods and data analysis

Snow surveys included in this summary vary from 10 to 44 samples per forest type and opening, range in frequency from twice a season to weekly over a period of months, and include one to three years of record. Differences in sampling intensity affect the differences in absolute SWE values between sites; however, comparison of F:O ratios reduces this variability. 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 removal.

Maximum SWE or SWE at the onset of the continuous melt period is often taken as SWE on April 1st. While the actual maximum may precede or follow this date, the recorded maximum will ultimately be a function of snow survey dates relative to actual maximum date (Table 4). For this summary, maximum SWE measurements provided on or nearest to April 1st were chosen to represent water available to generate spring melt runoff.

Table 4. The date of maximum SWE versus 1 April SWE and the 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).

Forest Cover	Year	Date of April 1 SWE minus date of max SWE	Ablation Rate (mm d^{-1}) 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)

Ablation rate is influenced by the period over which it is calculated. For example, in the open at Mayson Lake the average melt rate in 2007 was 6.6 mm d^{-1}, whereas the maximum ablation rate over a single week (the minimum sampling frequency) was 13.8 mm d^{-1} (Table 4). Describing ablation as a ratio of that in the forest to the open reduces differences between average and the maximum weekly ablation rates. For example, although the maximum weekly ablation rate in the intermediate red pine stand was 12.0 mm d^{-1} compared with the seasonal average of 5.6 mm d^{-1}, the ratio of forest to open was 0.74 for both the maximum and average (Table 4).

Interpreting differences between variables describing snow, stand, and attack conditions is thus key to collating study results for broader extrapolation.

SUMMARY

Snow surveys on the Interior Plateau of BC show a wide range of changes in snow accumulation and ablation as lodgepole pine stands attacked by mountain pine beetle turn from green to red to grey and become increasingly defoliated. Averaging values across studies, while helpful in communicating overall results, masks this inter-site variability. Compiling data from diverse projects over a broad geographic area is complicated by spatial variability in snow accumulation and melt, by differences among and within individual stands of the same inventory classification, and by the research methods applied. The development and utility of forest land and water management guidelines based on the results of multiple research projects depends, in part, on the careful description of forest composition, canopy attributes, and tree condition – including both the main canopy and understorey. The use of standardized snow sampling techniques for survey design and measurement methods will also improve our ability to conduct multi-study syntheses. The need for snow accumulation and ablation information over broad spatial scales, and for best management practice guidelines following extensive forest disturbances such as the current mountain pine beetle epidemic, highlights the need for coordinating research efforts among professionals and agencies prior to project establishment.

ACKNOWLEDGEMENTS

The authors thank Pierre Beaudry, Dan Bewley, Don Dobson and Pat Teti for providing project reports, snow survey data, descriptions of study sites and methods, and reviews of the summary tables included in this paper. Thanks also to Todd Redding and Graeme Hope for their reviews and helpful comments.

REFERENCES

Beaudry, P. 2007. Snow surveys in Supply Block F, Prince George TSA–January to March, 2007. Unpublished report submitted to Canadian Forest Products Ltd., Prince George Div., March 30, 2007.

Boon, S. 2007. Snow accumulation and ablation in a beetle-killed pine stand in northern interior British Columbia. B.C. J. Ecosystems Manag. 8(3):1–13. http://www.forrex.org/publications/jem/ISS42/vol8_no3_art1.pdf

Boon, S. 2009a. Impact of mountain pine beetle infestation and salvage harvesting on seasonal snow melt and runoff. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Mountain Pine Beetle Working Paper 2008-24. 28 p.

Boon, S. 2009b. Snow ablation energy balance in a dead forest stand. Hydrological Processes. DOI: 10.1002/hyp.7246.

Dobson, D. 2008. Border Lake snow survey (Year 2 – 2008 report). Dobson Engineering Ltd., Kelowna, B.C.

Metcalfe, R.A. and J.M. Buttle. 1998. A statistical model of spatially distributed snowmelt rates in a boreal forest basin. Hydrol. Proc. 12(10-11):1701.

Mitchell, R.G. and H.K. Preisler. 1998. Fall rate of lodgepole pine killed by the mountain pine beetle in central Oregon. Western Journal of Applied Forestry 13:23–26.

Pomeroy, J.W., D.M. Gray, N.R. Hedstrom, and J.R. Janowicz. 2002. Physically based estimation of seasonal snow accumulation in the boreal forest. Proceedings of the 59th Eastern Snow Conference, Stowe, Vermont, pp. 93-108.

Redding, T., R. Winkler, D. Carlyle-Moses, and D. Spittlehouse. 2007. Mayson Lake study examines hydrological processes. LINK 9(2):10-11.

Safranyik L. and W.R. Wilson. 2006. The mountain pine beetle: a synthesis of biology, management, and impacts on lodgepole pine. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. 304 p.

Skidmore, P., K. Hansen, and W. Quimby. 1994. Snow accumulation and ablation under fire-altered lodgepole pine forest canopies. Proceedings of the 62nd Western Snow Conference, Santa Fe, New Mexico. pp. 43-52.

Teti, P. 2009. Effects of overstory mortality on snow accumulation and ablation. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Mountain Pine Beetle Working Paper 2008-13. 34 p.

Toews, D.A.A. and D.R. Gluns. 1986. Snow accumulation and ablation on adjacent forested and clearcut sites in southeastern British Columbia. Proceedings of the 54th Western Snow Conference, Phoenix, Ariz., April 15–17, 1985, pp.101–111.

Winkler, R.D. 2001. The effects of forest structure on snow accumulation and melt in south-central British Columbia. PhD thesis. Univ. British Columbia, Vancouver, B.C.

Winkler, R.D. and R.D. Moore. 2006. Variability in snow accumulation patterns within forest stands on the interior plateau of British Columbia, Canada. Hydrological Processes 20:3683–3695.

Winkler, R.D., D.L. Spittlehouse, and D.L. Golding. 2005. Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in southern British Columbia. Hydrological Processes 19:51–62.