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Snow accumulation and ablation response to changes in forest structure and snow surface albedo after attack by mountain pine beetle

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Abstract:

This study quantified changes in snow accumulation and ablation with forest defoliation in a young pine stand attacked by mountain pine beetle, a mature mixed species stand, and a clearcut in south-central British Columbia. From 2006 to 2012, as trees in the pine stand turned from green to grey, average canopy transmittance increased from 27% to 49%. In the mixed stand, transmittance remained constant at 19%. In 2009, the year of greatest needle loss, average snow surface litter cover in the pine stand was 29% (range 4 – 61%), compared to ≤9% in other years and over double that in the mixed stand. By 2012, litter accumulation in the now-grey pine stand was only a sixth of that in the mixed stand. Inter-annual variability in the weather had the greatest effect on snow accumulation and ablation, with the greatest differences between both forested stands and the clearcut occurring in 2010, the year of lowest SWE. Differences in snow accumulation between the pine and mixed stand increased in 2010 as a result of decreased snow interception in the young stand after needlefall. Average ablation rates in the attacked stand were most different from the mixed stand in 2009 and 2012, the years with the largest and smallest over-winter needle loss, respectively. This study shows that grey, non-pine, and understory trees moderate snow response to changes in the main canopy. It also highlights the complex interrelationships between ecohydrological processes key to assessing watershed response to forest cover loss in snow dominated hydrologic regimes. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS forest–snow interactions; snow accumulation; snow ablation; mountain pine beetle; forest litter; snow albedo

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INTRODUCTION

Snow accumulation and ablation in forested regions are largely driven by weather and forest structure, both of which affect snowfall patterns, snow interception, radiation transmission, and forest litter production (Link and Marks, 1999). The frequency and intensity of storm systems and snowfall amount affect the canopy's interception capacity (Schmidt and Gluns, 1991; Hedstrom and Pomeroy, 1998; López-Moreno and Stähli, 2008). Snow intercepted by the canopy can be stored, unloaded to the ground, redistributed by high winds, or sublimated back into the atmosphere (Pomeroy and Goodison, 1997), affecting snow accumulation on the ground. Radiation transmission through the canopy is inversely proportional to canopy density, with subsequent effects on snow ablation given the dominant role of radiation in the snowmelt energy balance. Wind speed and consequently the sensible and latent heat transfer of energy are reduced under the forest canopy. The energy balance is also affected by forest litter production, which can reduce snow surface albedo and enhance melt (Hardy *et al.*, 2000; Winkler *et al.*, 2010).

Since 1994, 17.5 million ha of lodgepole pine (*Pinus contorta* Dougl.) dominated forests in British Columbia have been attacked by mountain pine beetle (MPB). More than 6 million ha of timber in Alberta are susceptible, and lodgepole pine stands throughout the western United States have either been affected or are at risk. The needles of lodgepole pine trees killed by MPB rapidly fade from green to greenish-yellow due to moisture loss, with tree crowns generally fading to bright red and brown by late summer in the year following attack. Depending on the weather in subsequent years, crowns turn grey as needles and fine branches are lost (Mitchell and Preisler, 1998). The symptoms of tree mortality depend on the season and severity of attack, tree age and vigour, and the weather. Trees killed by MPB retain some dead needles 3 to 5 years following attack (Safranyik and Wilson, 2006). The loss of needles and fine branches, and eventual blowdown, increases litter on the forest floor and reduces canopy density (Mitchell and Preisler, 1998; Winkler *et al.*, 2010).

Extensive forest die-off and large-scale changes in forest structure raise concerns regarding effects on snow accumulation and ablation, and the potential for associated changes in snowmelt-generated streamflow

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(Boon, 2009; Adams *et al.*, 2011; Pugh and Small, 2011; Boon, 2012). Given the rapid rate of infestation and the operational demand for information regarding salvage harvesting effects on water resources, early studies were generally conducted over short timeframes (1–2 years), most under less than ideal experimental conditions. For example, burned stands have been used to simulate beetle-killed stands, space has been substituted for time to represent changing forest structure, mixed species stands are used to represent the live stand condition in the absence of unattacked pine, and most studies have focused on single stands typical of an attack class with multiple survey sites in each stand used as pseudo-replicates of each condition (see Winkler and Boon, 2009).

Recent research in Colorado (Pugh and Small, 2011) included multiple pairs of proximate live and attacked stands providing opportunities for statistical comparison. However, this study was also complicated by changes in forest and weather conditions over the 2-year period.

Forest structure, particularly canopy density, has consistently been shown to be well correlated with snow accumulation and melt (Varhola *et al.*, 2010), the interrelationships varying with slope and aspect (Ellis *et al.*, 2011). In stands affected by MPB, studies have generally shown increased snow accumulation in grey relative to green stands as a result of reduced interception and sublimation losses, and increased ablation rates due to increasing shortwave radiation transmission to the snow surface as canopy density decreases (Boon, 2009; Winkler and Boon, 2009; Pugh and Small, 2011).

No published studies have documented changes in forest cover, snow accumulation, and ablation over time as trees in the same stand(s) turn from green to grey. This information is key to quantifying the trajectory of snow processes in the years following MPB attack, and to separate the effects of inter-annual variability in weather from changes in forest cover. These data are necessary to improve our ability to model watershed response to MPB, and to inform decisions regarding the balance between salvage harvesting and retention of attacked stands across the landscape.

The goal of this study was to quantify snow accumulation and ablation response to changing forest cover and snow surface albedo over a 7-year period during and after an MPB attack. During this time period, we quantified changes in forest cover, canopy transmittance and forest litter production, and snow accumulation and ablation, in a young, thinned, and pruned lodgepole pine stand, a mature mixed stand, and a clearcut. Results provide key information for modeling changes in stand structure and snow response to MPB over time and regarding effects of insect infestation on snow accumulation and ablation relative to the effects of salvage logging. Forest and water management decisions specifically require quantitative data on changes in snow processes as stands turn from green to grey, the timing of these changes, the influence of secondary stand structure, and whether standing dead trees affect snow processes differently than green trees.

STUDY SITE

This study was located near Mayson Lake, BC, approximately 50 km northwest of Kamloops, BC (Figure 1) (Winkler *et al.*, 2010). Stand-scale monitoring in this area

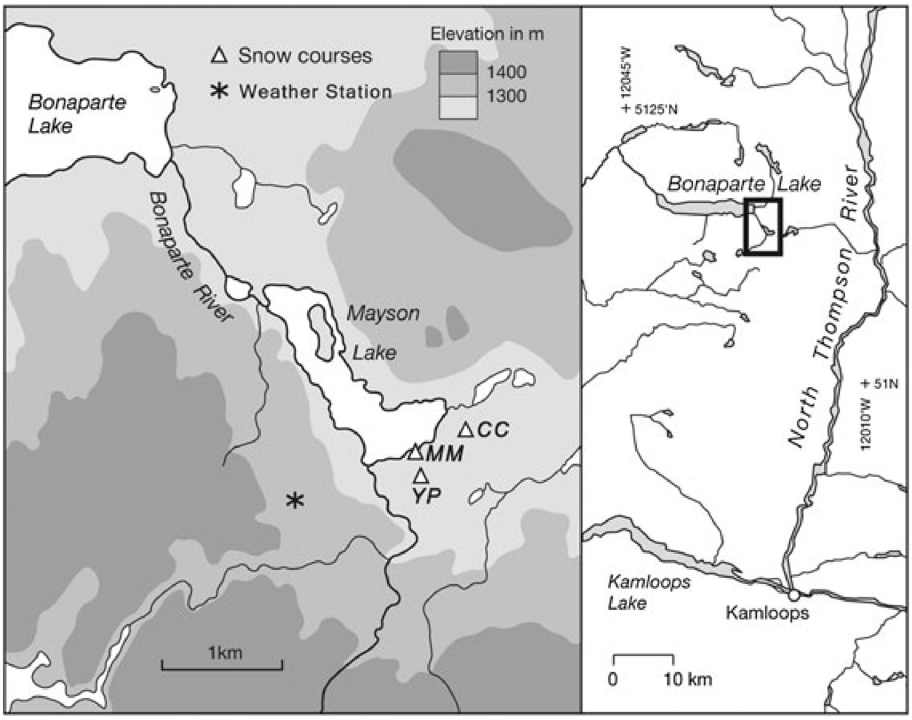

Figure 1. The Mayson Lake snow research area and the location of the clearcut (CC), young pine (YP), and mature mixed species (MM) study stands. Weather stations were located in each study stand and in a regenerated clearcut (*)

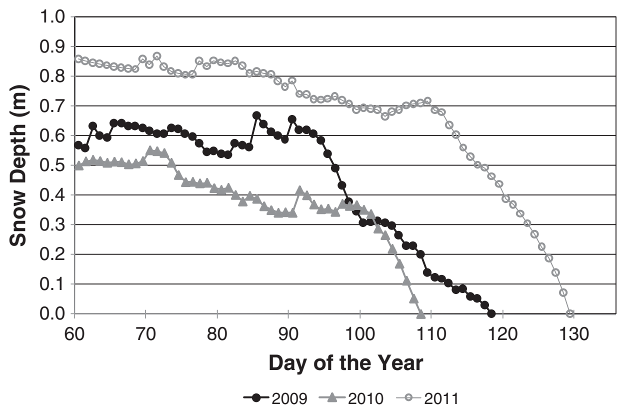

Figure 2. Snow depth at the clearcut climate station from early March to mid May 2009 (year of greatest needle loss), and for 2010 and 2011 (years of lowest and highest snowfall, respectively)

began in 1995 and was originally undertaken to quantify the effects of forest re-growth on snow processes (Winkler *et al*., 2005; Winkler and Moore, 2006). In 2005, lodgepole pine trees >14 cm in diameter were attacked by MPB throughout the study and surrounding area. Since then, research has focused on the effects of stand mortality on hydrologic processes.

The study area is located at 1270 m asl on gently rolling terrain in the Montane Spruce dry mild biogeoclimatic subzone (BC Ministry of Forests and Range, 2008) (51.13°N, 120.24°W). On average, it receives 560 mm of precipitation a year, of which approximately 40% falls as snow. Snow accumulates from late October until March or early April, to depths of 0.45 - 0.84 m in the clearcut. In some years, periodic ablation reduces SWE prior to the main melt season; however, April 1st SWE is taken as an index of the maximum accumulated snow that will contribute to spring runoff. The snowpack disappears between mid April and early May (Figure 2).

Three sites located within 3 km of each other were selected for this study (Figure 1): a young (~35 years old), thinned, and pruned lodgepole pine stand (YP); a mature mixed (MM) stand of Engelmann spruce (*Picea engelmannii* Parry), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt) and lodgepole pine; and a recent clearcut (CC). The mature mixed species stand was chosen to represent a typical post-MPB green stand since no unattacked pure lodgepole pine stands remained in the study region.

The main canopy (dominant and codominant trees) of YP is characterized by widely spaced, 12.7 m tall lodgepole pine at 1000 stems per hectare (sph), with a basal area of ~18 $m^2 ha^{-1}$ (Table I). The understory (intermediate and suppressed tree layer) is comprised of smaller trees (averaging 4.2 m tall) of pine (53%), Engelmann spruce (33%) and a minor component of subalpine fir (14%). In contrast, MM is a much denser stand (3631 sph) of larger diameter trees (basal area of 50 $m^2 ha^{-1}$) and is comprised of mixed species (17% pine, 35% spruce and 48% subalpine fir). Approximately 20% of the total stems form the 23.4 m tall main canopy, while the remaining trees, predominantly (93%) Engelmann spruce and subalpine fir on average 6 m tall, form the substantial intermediate and suppressed layer. The CC was logged in 2006, and all regeneration is <1 m. Over the study period, 58% of the pine trees in YP and 20% in MM turned grey.

METHODS

Weather

Weather data were collected in a regenerated CC approximately 0.5 km west of the study stands from 2006 to 2010 (Figure 1) and in the study CC from winter 2009 to 2012. Comparison of winter 2009–2010 data between the two stations showed negligible differences. Recorded variables included incident and reflected shortwave radiation (LiCor LI200), air temperature and humidity (2 m) (Vaisala HMP35C), wind speed (2 m) (MetOne 013 cup anemometer), snow temperature (Type K thermocouples at 0, 0.2, and 0.5 m), snow surface temperature (Apogee infrared radiometer) and snow depth (Campbell Scientific Inc. SR50A). Weather stations in YP and MM also recorded air and snow temperature, snow surface temperature and snow depth using the same instrumentation. Data were recorded on Campbell Scientific Inc. 10X data loggers scanning every minute and providing hourly and daily averages. Average, maximum, and minimum daily air temperature; average and maximum daily wind speed;

Table I. Forest characteristics by species and canopy layer (D/C dominant and codominant trees; I/S intermediate and suppressed trees >1 m tall) in the young pine (YP) and mature mixed (MM) stands in 2006

Site	Species	Basal area ($m^2 ha^{-1}$)	Stems per hectare (% of canopy layer)			Tree height (m)		Diameter (cm) at 1.3 m	
			All Trees	D/C	I/S	D/C	I/S	D/C	I/S
YP	All	18.6	1288	688	600	12.7	4.2	17.5	4.8
	Pine	17.6	1000 (78)	681 (99)	319 (53)	12.7	5.7	17.4	6.6
	Spruce	0.7	200 (15)	0	200 (33)		3.9		4.9
	Subalpine fir	0.3	88 (7)	6 (1)	82 (14)	12.4	2.2	23.3	1.6
MM	All	50.1	3631	756	2875	23.4	6.0	24.1	6.2
	Pine	25.0	613 (17)	419 (55)	194 (7)	24.6	10.6	26.7	13.3
	Spruce	14.7	1263 (35)	213 (28)	1050 (36)	22.5	7.0	24.6	7.3
	Subalpine fir	10.4	1756 (48)	125 (17)	1631 (57)	21.8	5.7	20.6	5.7

average daily solar radiation; and accumulated degree-days above zero were calculated for each year of the study from March 1 to the date snow disappeared at the CC weather station. Maximum snow depth, SWE, and date the snow pack became isothermal were also defined.

Forest structure

Trees in YP and MM were inventoried in 2006 using standard forest measurement techniques (Forestry Undergraduate Society, 2005) in 3.99 m radius fixed area plots centred on each of 32 permanent sample points laid out in a 15 × 15 m grid (8 × 4 points) covering approximately 0.5 ha in each stand. Tree condition was assessed visually as green, red, or grey in 2006, 2008, and 2011. To quantify forest canopy loss and provide an indication of litter sources, hemispherical photographs of the canopy were taken at every second snow sampling station in YP and MM, as detailed in Winkler *et al.* (2010). Photographs were taken in late summer 2007 and repeated each spring until 2012. Photos were taken under completely overcast skies near the same date in May each year using a Nikon 4500 camera with a FC-E8 fisheye lens converter. The camera was oriented so that the top of each image was north and the lens plane was levelled with a bubble level on the lens cap. In order to minimize user bias, photography and photo analysis was completed by the same person throughout the study and threshold selection for converting the blue channel to bitmap black and white was automated using SideLook 1.1.01 (Nobis, 2005; Nobis and Hunziker, 2005). Bitmap images output from Sidelook were compared with the original photo to assess accuracy, and contrast in the original image was adjusted in the few cases where this was necessary. Photos were analysed with Gap Light Analyser 2.0 (Frazer *et al.*, 1999), using April 1 to May 15 as the time period of interest, to determine plant area index (PAI; needles, branches, and stems) and total percent transmittance. Changes in stand structure attributes over the study period were quantified using canopy transmittance and tallies of total stems per hectare (Tsph) as well as stems in each canopy layer by species. Variables used to describe the distribution, volume, and density of stems and canopy are indicative of relative interception losses and energy input to the snow surface within and between stands. Stem data are readily accessible operationally and to modellers through forest inventory databases and canopy transmittance is commonly available for long-term research installations.

Forest litter

Litter accumulating in and on the snowpack was collected in litter frame pairs placed at three permanent stations in each stand in the winters of 2009 to 2012. Litter frames were constructed of 1.25 cm white PVC pipe and window screen, with inside edges measuring 60 × 90 cm (0.54 m^2). One frame of each pair was placed at the ground surface in late October prior to snowfall. The second frame was placed on the snowpack surface in late March, directly above the ground frame. At the end of the melt season, litter from each frame was dried and weighed to determine the proportion of total litter fall accumulated within the pack prior to melt, and that which fell during melt, per unit area (litter weight divided by frame area).

To address the high spatial variability in litter fall observed across the forested study sites, percent litter cover was also calculated using photographs of an unscreened litter frame at every second snow survey station ($n = 16$) on three to four dates during the 2009 to 2012 melt seasons. Litter cover was also measured at three frames in each stand in 2008 (see Winkler *et al.*, 2010); these data are included in this study. Photos were analysed and percent litter cover calculated using Adobe Photoshop, ImageDIG and SYSTAT 11, as described in Winkler *et al.* (2010). Only those frames with >50% snow cover were analysed, and litter cover was calculated only from the snow covered portion of each frame.

Snow surface albedo

Snow surface albedo was measured following Winkler *et al.* (2010) using a pair of up- and downward facing LiCor LI200 silicon diode pyranometers. Pyranometer output was corrected for differing spectral response under canopies and for reflected energy (Henneman and Stefan, 1998) by comparison with a Kipp and Zonen CM6 albedometer during the same time of day that study measurements were collected (CC: $y = 1.27x - 0.24$, $r^2 = 0.80$; $SE_e = 0.008$; MM: $y = 1.05x - 0.08$, $r^2 = 0.54$, $SE_e = 0.006$). The relative percent difference in albedo measured with the silicon diode pyranometers averaged 2% and 11% higher in CC and MM, respectively, than that measured with the thermopile-based instruments and did not exceed 5% and 13% in each stand, respectively.

Albedo was measured at every second snow survey station ($n = 16$) in each stand on the same dates as litter cover measurements from 2009 to 2012, except in CC in 2011 when measurements were only made at the three litter traps. These spatially distributed surveys expanded on initial measurements collected in 2008 at the three litter trap locations in each stand (Winkler *et al.*, 2010). The pyranometers were mounted on an aluminum pole held 1.5 m from the observer at ~1.2 m above the snowpack (i.e. the height where ~95% of the field of view of the downward facing pyranometer fell within the 1.5 m radius of the centre of the litter frame). Ten measurements at 1 s intervals from each station were averaged and stored in a Campbell Scientific Inc. 21X data logger. Measurements were collected between 0900 and 1500 PST; only data collected during overcast conditions were used so as to avoid the effects of sunflecks on the snow surface but not on the incident sensor (and vice versa). Data were only used where the area within the frame had >50% snow cover. The up- and downward facing pyranometer values were compared prior to each survey period to ensure stability of the calibration.

Snow accumulation and ablation

From 2006 to 2012, SWE was measured at each of the 32 permanent sample points in each stand. Surveys generally began on March 1 and were conducted biweekly to weekly throughout the melt period. Snow survey station 1 was located at random within each stand while ensuring that all sample points were at least 50 m from any stand edge. Measurements were made within a maximum 1 m radius of each sample point marker using a standard Federal snow tube. SWE on April 1 was used in all stand comparisons since this is the date commonly used as an annual index for water supply and flood forecasting. On average, April 1 SWE was 5% less than maximum SWE on all survey dates, varying from 0 to 13% less than maximum SWE. The largest differences occurred in 2007 as a result of an early ablation period prior to the main melt season and in 2008 due to continued snow accumulation after April 1 prior to a late melt.

The fraction of snow intercepted by the canopy and lost back to the atmosphere in each year was calculated using the stand average SWE value on the survey date prior to the snowpack becoming isothermal (measured at the weather stations), which varied from day 64 in 2007 to day 98 in 2008. This estimate of interception loss assumes negligible sublimation from the snow surface and no melt prior to that snow survey date. Weather station data from CC, MM and YP were used to confirm these assumptions by tracking snowfalls and changes in snow depth and temperature.

Seasonal average ablation rates (AARs) were calculated for each plot by dividing SWE at the onset of the continuous melt period by the number of days to complete snow removal. The number of ablation days was determined by extrapolating SWE to zero in the final sampling period based on the ablation rate over the previous period (Winkler *et al.*, 2010). This method may result in a 1–2 day early predicted snow disappearance date; however, since the same method was applied uniformly to all stands in all years, it has little effect on the relative differences in average seasonal ablation rates.

Data analysis

Data summaries and statistical analyses were completed using SYSTAT 11, with statistical significance for all tests set to $\alpha = 0.05$, except for evaluation of correlation between variables where $\alpha = 0.01$. Data distributions were assessed graphically and tested for normality using the Shapiro–Wilks' W test, and Levene's test was used to check for homogeneity of variance. Since neither April 1 SWE nor AARs were normally distributed in all years and variances were not equal, the non-parametric Kruskall–Wallis test was used to test for differences between years and stands. Correlations, described by adjusted r^2 values, between canopy transmittance, snow surface conditions represented by either litter cover or albedo, SWE and AAR, both within and between stands, were assessed using single and multiple regression techniques based on general linear models. Non-linear data were transformed prior to use in linear regression.

RESULTS

Weather

Over the 6-year study period (2006–2012), maximum daily March 1 to end of melt air temperature in CC averaged 5.3 °C and ranged from 3.9 °C in 2009 to 6 °C in 2006 and 2010 (Table II). Minimum daily air temperatures averaged −7.5 °C and were lowest in 2009 (−9.4 °C). Accumulated degree days above zero during the snow survey period were highest in 2006 and 2007 and lowest in 2009. Average daily solar radiation varied by ±10% between years; wind speed also varied by ±10% between years, averaging 2.1 m s^{-1} over the snow survey period (SD = 0.6).

In YP and MM, average daily air temperatures were generally 0.4 °C and 0.8 °C lower, respectively, than in CC. In 2007, prior to any significant changes in forest structure,

Table II. Weather conditions from March 1 to end of melt period for 2006 to 2012 at the clearcut (CC) climate station

	2006	2007	2008	2009	2010	2011	2012
	Average (SD)						
Average daily air temperature (°C)	−0.5 (4.2)	−0.1 (3.9)	−1.8 (4.3)	−2.6 (5.7)	−0.1 (3.5)	−0.7 (3.5)	−1.2 (4.1)
Maximum daily air temperature (°C)	6 (4.2)	5.7 (4.3)	4.9 (4.4)	3.9 (6.1)	6.1 (4.3)	5.1 (3.6)	5.6 (4.5)
Minimum daily air temperature (°C)	−6.9 (5.3)	−6.2 (5)	−8.7 (5.4)	−9.4 (6.1)	−6.8 (4.7)	−6.4 (5)	−7.8 (5.1)
Accumulated degree-days above zero with snow	86	95	79	52	67	72	68
Average relative humidity (%)	76 (12)	70 (12)	68 (10)	66 (13)	69 (12)	74 (12)	57 (16)
Average daily solar radiation (MJ m^{-2} d^{-1})	13.2 (4.7)	11.7 (4.8)	14.1 (4.4)	13.9 (5)	12.8 (2.9)	14 (5.1)	13.3 (5.4)
Average daily wind speed (m s^{-1})	2.1 (0.8)	2.3 (0.4)	2.1 (0.4)	1.8 (0.7)	2.3 (0.7	2 (0.5)	2.1 (0.6)
Maximum daily wind speed (m s^{-1})	5.5 (2.1)	6 (1.1)	5.6 (0.9)	5 (1.9)	6.6 (1.3)	6 (1.1)	6.3 (1.3)
Maximum SWE (mm) from clearcut survey	233 (28)	228 (28)	226 (23)	206 (31)	154 (21)	266 (27)	225[b]
Date of maximum snow depth	18 March	2 March	31 March	28 March	12 March	24 March	14 March
Date of maximum SWE	30 March	5 March	8 April	2 April	16 March	1 April	26 March
Date of isothermal pack	31 March	10 April[a]	10 April	7 April	22 March	9 April	27 March
Date snow disappeared	26 April	1 May	12 May	29 April	19 April	10 May	23 April

[a] The snowpack was isothermal for several days on March 8 and 26 and continuously after April 10.

[b] Estimate from snow sensor data and April 3 snow survey.

maximum daily air temperature in both YP and MM was strongly related to both the daily maximum ($r^2 = 0.98$ and 0.96, respectively) and daily minimum air temperature in CC ($r^2 = 0.97$ and 0.98). These relationships were used to predict maximum and minimum air temperatures in YP and MM in subsequent years, assuming no change in forest structure. Differences between predicted and actual temperatures showed slight warming in YP relative to the CC in 2010 and 2011 (by 1.1 and 0.6 °C, respectively), while no change was observed in MM. Measured daily minimum air temperatures were not significantly different from predicted values.

The date on which the snowpack in CC became isothermal varied between March 22 in 2010 and April 10 in 2007 and 2008, differing by no more than three days between MM and either YP or CC. Wind speed measured in YP in 2012 was 40% of that in CC, whereas wind speed under the dense canopy of MM was negligible the majority of the time (Winkler *et al*., 2005).

Forest structure

In 2006, 1 year following MPB attack, 100% of the trees in YP remained green (Figure 3). By the spring of 2007, 55% of the trees (95% of the main canopy) were red, and by 2011, 58% (96% of the main canopy) were grey; the rest remained green (Figure 3a). Of the green trees, most (38%) were in the understory and included both pine and non-pine species (Figure 3b). Few trees in YP (19 sph) blew down over the study period.

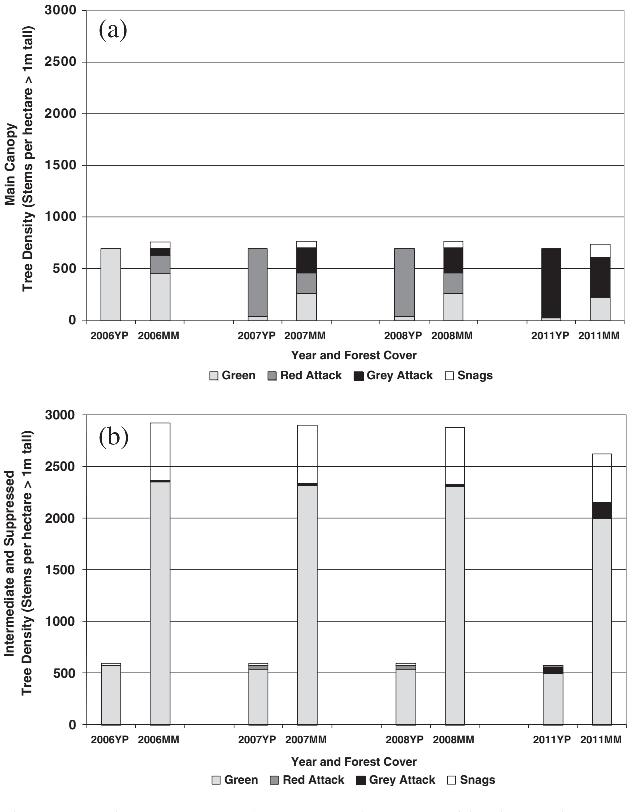

Figure 3. Main canopy (a) and understory (b) tree condition in the pine (YP) and mature mixed species (MM) stands, in fall 2006 and in spring 2007, 2008, and 2011. Note that tree density declines slightly in MM due to blowdown

In 2006, 76% of the total stems in MM were green (Figure 3). Snags (trees killed by previous insect attacks) comprised 17% of the total stems. By 2011, 66% of the total stems remained green, while nearly all of the pine in the main canopy (53% of the total main canopy stems) had turned grey (Figure 3a). However, trees in the understory remained largely unchanged (76% green) (Figure 3b). Approximately 9% of the trees standing at the beginning of the study either blew down or were crushed by blowdown during the study period.

Hemispherical photo analyses show that PAI in YP decreased from 1.9 to 0.9 between August 2007 and June 2011. Over the same time period, PAI in MM showed minimal change from 2.5 to 2.1. In late summer 2007 and spring 2008, when the YP canopy was red but had not yet lost its needles, average canopy transmittance was 28% and varied from 17 to 58%. By spring 2011, most needles had been lost, and the stand had turned grey, increasing transmittance to 49% (range 19 to 66%) (Figure 4). The largest incremental increase in transmittance (7%) occurred between spring and fall 2009. When combined with additional canopy loss (3%) in early winter of 2009, average transmittance increased from 35% to 45% between spring 2009 and spring 2010 (Table III). Canopy transmittance in YP showed no change in 2012. In MM, where pine comprised 55% of the main canopy and 7% of the understory, average canopy transmittance was 18% (range 12 to 27% within the stand) and did not change over the 2007 to 2012 study period; minor inter-annual variability reflects measurement error (Figure 4).

Forest litter

No litter fell into any of the frames in CC during the study period. In contrast, over 200 g m^{-2} of litter was collected in YP in 2009 and approximately 100 g m^{-2} in MM (Figure 5). In all years, YP litter consisted of 97% pine needles, while MM litter was comprised of 73%

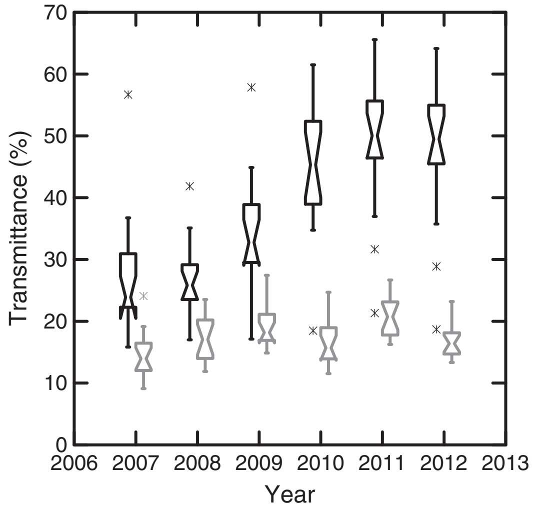

Figure 4. Percent transmittance in the pine (YP; black box) and mixed species (MM; grey box) stands prior to snowfall in 2007, and following snow disappearance each spring to 2012. Values are calculated from hemispherical photographs, $n = 16$ for each stand

Table III. Average canopy transmittance measured in late summer of 2007 and at the end of snowmelt each subsequent year and percent litter cover and albedo measured from early to late melt 2008 to 2012 in the young pine (YP) and mature mixed (MM) stands. No litter was observed on the snow surface in CC at any time during the study. Litter cover was measured at three locations in each stand in 2008 and at 16 snow survey stations per stand in all other years. Transmittance, litter cover, and albedo were measured at 16 snow survey stations throughout the study

Year	Day	% Transmittance		% Litter cover		Albedo		
		YP Avg (SD)	MM Avg (SD)	YP Avg (Range)	MM Avg (Range)	YP Avg (Range)	MM Avg (Range)	CC Avg (Range)
2007	215	27 (10)	15 (4)					
2008	101	29 (7)	17 (3)	5 (0–12)	0	0.69 (0.54–0.80)	0.69 (0.55–0.82)	0.78 (0.73–0.90)
	120			9 (5–14)	9 (7–12)	0.48 (0.38–0.56)	0.34 (0.26–0.43)	0.72 (0.63–0.75)
2009	92	35 (9)	20 (4)	0	0	0.70 (0.57–0.78)	0.72 (0.65–0.79)	0.80 (0.78–0.82)
	104			19 (0–54)	11 (5–19)	0.37 (0.23–0.48)	0.34 (0.25–0.41)	0.70 (0.63–0.76)
	111			29 (4–61)	19 (11–26)	0.23 (0.10–0.37)	0.30 (0.21–0.37)	0.51 (0.42–0.57)
2010	90	45 (10)	17 (3)	6 (0–27)	8 (2–15)	0.40 (0.24–0.47)	0.34 (0.21–0.42)	0.58 (0.54–0.62)
	102			1 (0–5)	2 (0–10)	0.42 (0.26–0.69)	0.48 (0.18–0.73)	0.56 (0.48–0.63)
2011	91	49 (11)	21 (3)	0 (0–1)	2 (0–6)	0.54 (0.47–0.60)	0.53 (0.45–0.59)	0.65 (0.64–0.67)
	104			0 (0–1)	4 (1–9)	0.51 (0.34–0.59)	0.51 (0.31–0.71)	0.67 (0.65–0.69)
	122			4 (0–8)	14 (9–23)	0.42 (0.34–0.48)	0.35 (0.30–0.43)	0.57 (0.56–0.57)
2012	95	48 (12)	17 (3)	0	0 (0–1)	0.60 (0.39–0.78)	0.60 (0.32–0.72)	0.64 (0.56–0.70)
	111			2 (0–4)	6 (3–14)	0.54 (0.37–0.93)	0.48 (0.26–0.83)	0.46 (0.37–0.60)

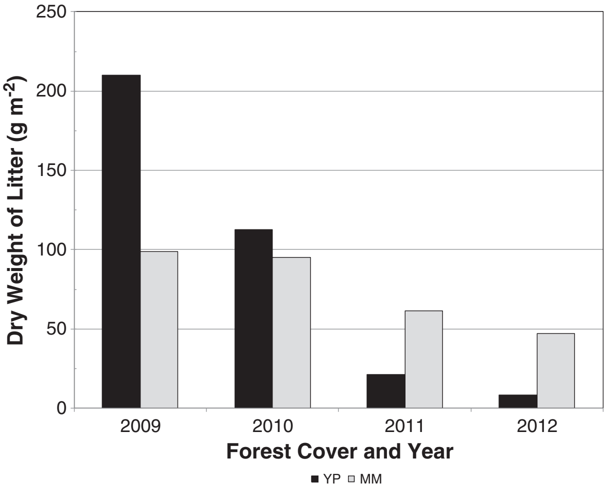

Figure 5. Total dry weight of forest litter collected from October through May in a young pine (YP) and mature mixed (MM) stand

spruce and fir needles, with the remainder including black tree lichen (*Bryoria* spp.), small twigs, cone scales, bark, and fine dust.

In all years, the surface traps collected less than 36% of the total litter from both traps, indicating that most litter accumulated in the snowpack prior to melt onset and became exposed during the melt season. The proportion of total within-snowpack litter accumulation ranged from 64 to 89%. The largest total litter accumulation occurred in 2009 in YP, and the least in both stands in 2012. In 2009, YP had more than twice the litter accumulation of MM (Table III; Figure 5). By 2012, when minimal canopy remained in YP, litter capture was only 1/6 the total captured in MM.

Snow surface litter cover was highly variable within and between stands, between years, and with time since the last snowfall. During the period of maximum needle loss in YP (2009), within-stand litter cover ranged from 0 to 61% (Figure 6). Much lower within-stand variability

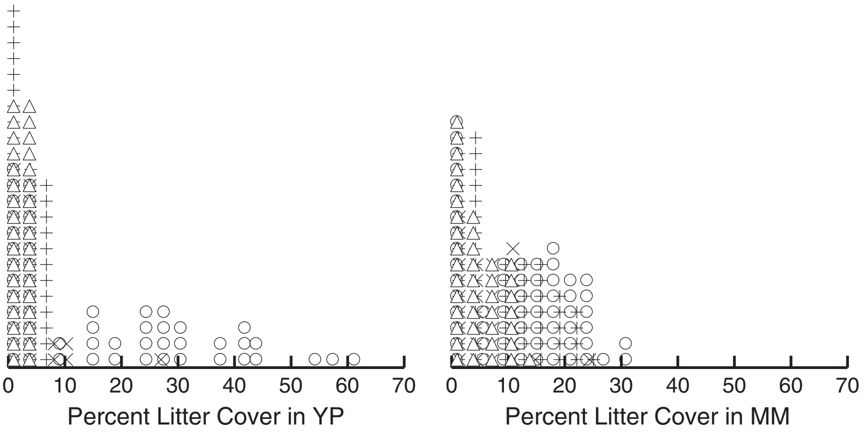

Figure 6. Percent litter cover measured at 16 snow survey stations in the young pine (YP) and mature mixed (MM) stands during mid-melt 2009 (O), 2010 (X), 2011 (+), and 2012 (▽). Each symbol indicates a station at which the given percent litter cover was measured; 16 stations in each stand every year

was observed in MM, which had a maximum range on any date of 15%. Litter cover in YP also varied with stage of attack (Figure 6). During mid-melt in 2008 (day 101), prior to red needle drop, litter cover at the three YP sampling sites was 5%, 9%, and 14%. By mid-melt 2009 (day 104), litter cover measured throughout YP averaged 19% (range 0–54%) and increased within a week to 29% (range 4–61%) (Table III). From 2010 to 2012, average YP mid-melt litter cover was ≤2% and coincided with the canopy becoming grey, while in MM, the average was between 2 and 6% in the same years. The effect of snowfall on periodic measurements of litter cover is clear in 2010, when a snowfall after the snow survey on day 90 resulted in an apparent decrease in litter cover by day 102 (Table III).

Snow surface albedo

On all survey dates, snow cover in CC had the highest albedo, ranging from 0.54 to 0.95 at the onset of melt and dropping to 0.42–0.76 during late melt (Table III). In YP, albedo ranged from 0.10 to 0.85 depending on time of year and attack stage. Figure 7 provides examples of litter cover during the late melt period. Early in the melt season in all years, litter cover was low and albedo high in both YP and MM. Average albedo was highest (48%) in 2012

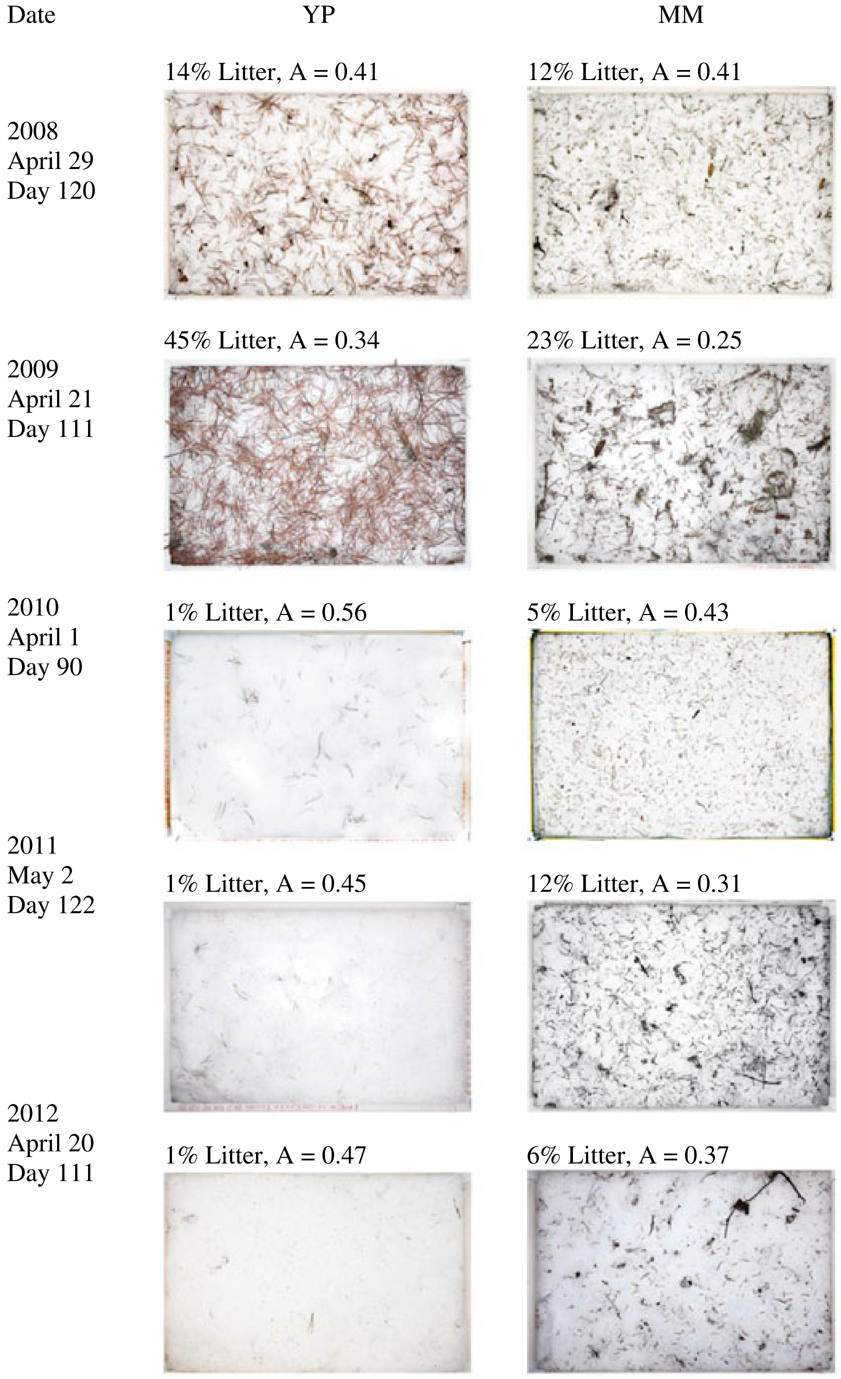

Figure 7. Examples of litter cover and albedo (A) in the young pine (YP) and mature mixed (MM) stands during melt of 2008 to 2012

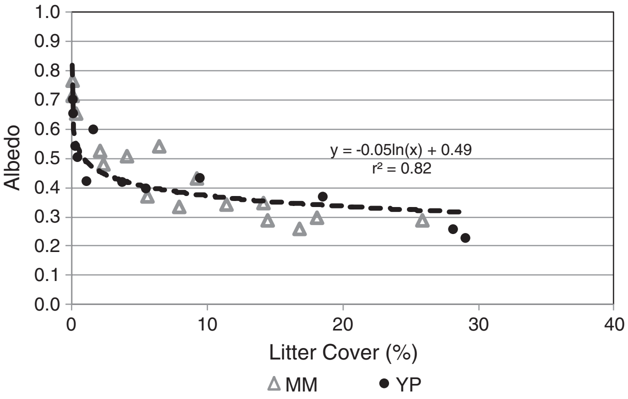

Figure 8. Average percent litter cover *versus* average snow surface albedo from 2008 to 2012 in the young pine (YP) and mature mixed species (MM) stands (averaged from $n = 16$ in each stand on each survey date in each year). No litter was observed in a nearby clearcut

when the YP canopy was grey retaining few needles and other fine canopy material, and lowest (23%) during late melt 2009 when snow surface litter cover was highest. By late melt 2009, litter cover in YP was on average 10% higher than in MM, and albedo was 7% lower. In 2011 and 2012, when minimal fine canopy material remained, litter cover in YP was 10% and 4% lower, respectively, than in MM, and albedo was ~7% higher (Table III).

Small initial accumulations of litter on clean snow resulted in a rapid decrease in albedo; as litter cover increased albedo was reduced further but the rate of change decreased (Figure 8). Log transformed litter cover (log(litter cover)) explained 44% of the variance in albedo among all stations in all stands on all survey dates. When YP and MM were considered separately, log(litter cover) explained a similar proportion of the variability in albedo within each stand on all survey dates (49% and 42%, respectively). When averaged for each stand on each survey date log(litter cover) explained 82% of the variance in stand average albedo. In a controlled lab experiment, Boon (unpub. data) found that the non-needle portion of litter collected in MM (i.e. *Bryoria* lichen) had a greater effect on albedo in the visible portion of the spectrum than either YP or MM needles alone, while the effect of both needle types was similar. This explains slight differences in albedo decay between YP and MM observed in the field when each stand is considered separately. Needle distribution across, and position relative to, the snow surface also affect albedo (Figure 7). In 2009, albedo was much higher in YP than in MM even though litter cover was lowest in MM. Litter in YP was observed to be clumped and elevated above a clean snow surface, whereas the mixed needle and finer litter in MM were evenly distributed across – and in direct contact with – the snow surface.

In addition to impurities, albedo is also affected by solar angle, snow depth, stage of metamorphism, and snowfall during the melt season. As noted previously, melt season snowfalls cover the litter and tend to mask the albedo reduction. On April 1, log(litter cover) explained 48% of the variance in albedo in YP and 63% of that in MM. By mid-melt, however, log(litter cover) explained only 12% of the variance in albedo in YP and was not statistically significant in MM. Snow depth recorded at all snow stations on all survey dates, indicative of stage of metamorphism and optical properties, explained 39% of the variance in albedo in CC, 19% of that in YP and 22% in MM. In a multivariate model including both log (litter cover) and snow depth, the latter was not significant relative to the influence of forest litter on snow albedo in YP, but together both variables explained 44% of the variance in albedo on April 1 in MM.

Snow accumulation and ablation

April 1 SWE was greatest in CC and lowest in MM in all years (Figure 9, Table IV). Differences between both forested stands and CC were significant in all years (Table V). SWE in CC ranged from 148 mm in 2010 to 263 mm in 2011: 29% below and 26% above the study period average, respectively. Relative to CC, SWE was on average 39% lower in MM and, prior to needle drop, 28% lower in YP. The largest differences between both forested stands and CC occurred in 2010, which was also the lowest snow year (Figure 9). Average SWE in YP was most similar to that in CC in 2009, and most different from that in MM in 2010 to 2012 (Table V). SWE in YP was significantly higher than in MM in all years except 2007 and 2008, both of which had average snowfall.

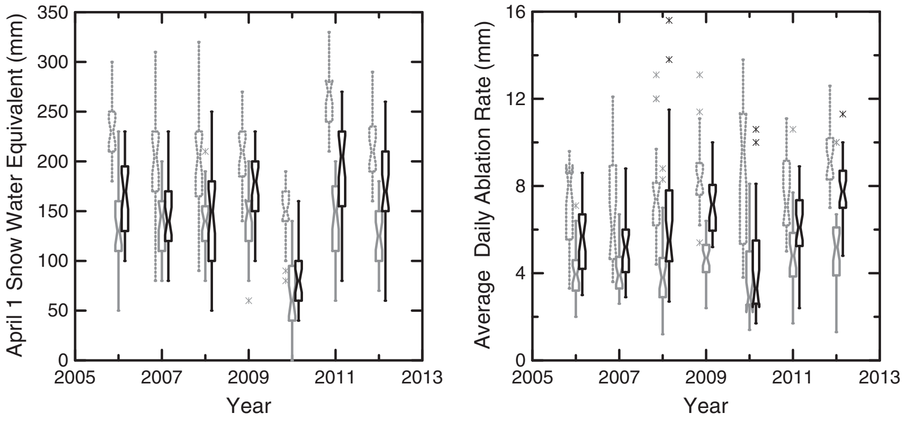

Figure 9. April 1 snow water equivalent and average ablation rates in the clearcut (CC, dotted grey), mature mixed (MM, grey), and young pine (YP, black) stands

Table IV. April 1 snow water equivalent (SWE; mm) and average ablation rate (AAR; mm d^{-1}) in the young pine (YP), mature mixed stand (MM) and clearcut (CC)

Variable	Stand	Year						
		2006 Avg (CV)	2007 Avg (CV)	2008 Avg (CV)	2009 Avg (CV)	2010 Avg (CV)	2011 Avg (CV)	2012 Avg (CV)
SWE	CC	233 (0.12)	198 (0.26)	196 (0.29)	206 (0.15)	148 (0.20)	263 (0.12)	212 (0.16)
	YP	166 (0.23)	144 (0.24)	143 (0.35)	175 (0.20)	88 (0.40)	191 (0.24)	174 (0.25)
	MM	135 (0.31)	137 (0.22)	140 (0.19)	144 (0.22)	65 (0.51)	140 (0.27)	127 (0.26)
AAR	CC	7.2 (0.25)	6.6 (0.34)	7.6 (0.28)	8.4 (0.19)	8.8 (0.37)	7.6 (0.23)	9.2 (0.16)
	YP	5.5 (0.28)	5.3 (0.29)	6.5 (0.48)	7.1 (0.19)	4.6 (0.54)	6.2 (0.25)	7.9 (0.17)
	MM	4.1 (0.30)	4.2 (0.25)	4.1 (0.43)	4.6 (0.21)	3.8 (0.51)	5.0 (0.36)	5.0 (0.38)

Table V. Ratios of average April 1 snow water equivalent (SWE) and average ablation rates (AAR) between the pine stand (YP), mature mixed stand (MM) and clearcut (CC) (shading indicates a statistically significant difference between stands at $p < 0.05$)

Snow Attribute	Year	Attack Class in YP	Ratio of SWE or AAR		
			YP:CC	YP:MM	MM:CC
SWE	2006	Green	0.71	1.23	0.58
	2007	Red	0.73	1.06	0.69
	2008	Red	0.73	1.03	0.71
	2009	Red	0.85	1.21	0.70
	2010	Red/Grey	0.59	1.35	0.44
	2011	Grey	0.72	1.36	0.53
	2012	Grey	0.82	1.37	0.60
AAR	2006	Green	0.76	1.33	0.57
	2007	Red	0.80	1.26	0.63
	2008	Red	0.86	1.48	0.55
	2009	Red	0.84	1.54	0.55
	2010	Red/Grey	0.52	1.21	0.43
	2011	Grey	0.82	1.24	0.66
	2012	Grey	0.86	1.58	0.54

Inter-annual variability in SWE was highest in CC and lowest in MM (Figure 9). On average, within-stand variability in SWE was higher in YP and MM than in CC (Table IV). In 2009, the year of greatest needle fall, within-stand SWE variability in YP was lower than in other years, but not in MM and CC. The highest within-stand SWE variability in both YP and MM occurred in 2010, the year of lowest snowfall, but not in CC.

Interception by – and loss of snow from – the forest canopy varied substantially both between years and between YP and MM. For MM, calculated interception averaged 38% of the CC SWE (range 18–47%), and for YP 25% (range 15–33%). Within-stand variability in measured SWE suggests an uncertainty of about 30% on the calculated interception loss.

AARs and inter-annual AAR variability were highest in CC (6.6–9.2 mm d^{-1}) and lowest in MM (4.1–5.0 mm d^{-1}) (Table IV). Within-stand variability in AAR was generally lowest in CC. The highest within-stand variability in AAR occurred in 2010 at all sites. Differences in AAR between both forested stands and CC were significant in all years: 19% lower in YP over the 3 years prior to needlefall, and 44% lower over all years in MM (Table V). Differences in AAR between YP and MM were also significant in all years except 2010, the year of lowest snowfall. The largest difference between YP and MM occurred in 2009 and 2012.

The date of snow disappearance in CC was approximately April 28 (day 118) in all years except 2008 and 2011, when snow lasted ~13 days longer. On average, snow in MM disappeared 3–11 days later than in CC. Snow in YP disappeared on average 1–4 days earlier than in CC and 5–12 days earlier than MM, except in 2010 and 2012 when snow disappeared in all stands within a period of three days.

DISCUSSION

Both forested stands remained green into 2007, 2 years after attack by MPB. Hemispherical photographs and stand survey data 3 years after attack (2008) indicate that most pine in both stands had turned red; however, trees retained their needles, and canopy transmittance remained unchanged. Pugh and Small (2011) also did not find a consistent difference in transmittance between green and red stands in Colorado. At Mayson Lake, red trees appeared to intercept snow similar to green trees, with inter-annual variability in YP tracking that in MM. From 2006 to 2008, April 1 SWE remained highest in CC and was up to 29% lower in YP and 42% lower in MM. The AAR remained relatively constant in MM and CC, indicating similar weather conditions each spring. In 2008, delayed melt resulted in a higher AAR later in the season in YP and CC, but not in MM. The greatest proportion of the within-stand variance in SWE in 2008 (prior to needle loss) was explained by canopy transmittance (30%), while the number of understory stems explained a small (19%) proportion of the variance in AAR.

Not until 4 years after MPB attack (2009) did sufficient needle loss occur to increase transmittance in YP. No change in transmittance was measured in MM, because the pine component of the main canopy was relatively small and the understory remained dense. By 2009, YP had the greatest number of litter frames with >30% litter cover, some reaching ~60% cover. This high litter cover of mainly red needles substantially reduced late melt season albedo relative to years with <10% litter cover. Late melt season albedo in MM was also somewhat lower due to higher litter cover in 2009 and 2011 than in 2008 or 2010. Litter production was not a result of exceptionally high winds in 2009 (see also Hardy *et al.* (2000)). The increased litter in both stands thus resulted from needle loss from the pine component of both YP and MM, and annual variability in needle loss from other tree species in MM. By 2012, litter fall was minimal in YP and in MM was similar to that in 2008, prior to needle loss from the pine trees in the main canopy.

Despite substantial needle loss in 2009, the effect of the 'greying' YP canopy on snow was similar to that when the trees were green and red. In 2009, Tsph and the number of stems in the main canopy, which indicate the number of stems with changed canopy, best explained the within-stand variance in SWE (47%). The greatest proportion of the variance in 2009 AAR (61%) was explained by canopy transmittance, total stems in the main canopy, and percent of the total stems that were pine which together represent both the loss of canopy and the density of unaffected stems at each survey station.

In 2010, the year of lowest snowfall, reductions in April 1 SWE in the forested stands relative to CC were the largest of all years, mainly a result of high interception losses (30 and 41% in YP and MM, respectively). Similar enhanced interception differences between forested and open sites in low snow years have been observed in other studies (Hedstrom and Pomeroy, 1998; Jost *et al.*, 2007). Differences in AAR between the forested stands and CC were also largest in 2010, due to less below-canopy solar radiation during the late March to early April melt season compared with the mid- to late April snowmelt in other years.

By 2011, absolute average canopy transmittance in YP had increased by 22% from the green phase (fall 2007). This was larger than the 11% increase reported by Pugh and Gordon (2012), who compared multiple stands with different attributes rather than measuring change in a single stand over time. As most needles from MPB killed trees had fallen from the canopy, snow surface litter in 2011, and albedo in 2011 and 2012, was similar to 2008 which had little needle loss.

Less interception is expected with a reduction in canopy volume (Pugh and Small, 2011), but the influence of needle loss on snow interception is complicated by the effects of inter-annual variability in winter snowfall and weather. The lack of a transmittance response to needle loss in MM suggests that there was minimal change to the canopy snow intercepting area and, therefore, any inter-annual variation in interception in this stand would be mainly due to inter-annual variation of the weather. Prior to needle fall, the calculated interception loss for 2006–2008 was 33% in MM and 26% in YP. Interception losses following needle drop (2010–2012) were 45% for MM and 27% for YP. The lack of a commensurate response in YP to MM under the same weather conditions suggests a reduction in YP snow interception associated with needle loss.

April 1 SWE and AAR in the forest stands and CC during the first 3 years after MPB attack (2006 to 2008) did not change substantially. By 2010, however, changes in SWE and AAR in the now-grey YP stand were apparent. Although the forest cover types in MM and YP were – of necessity – different, April 1 SWE differences between them were <20% until the post-needle loss period (2010–2012), following which the difference increased to ~36%. Differences in AAR between YP and MM were greatest in 2009, the year of highest litter cover in YP, and in 2012, when very few needles remained in the grey main canopy and ablation rates in YP and CC were higher than any other year. Although the 2010 AARs were not significantly different between YP and MM, and in 2011 were not greater than those observed while the canopy in YP remained green or red, the large difference between these stands in 2012 as well as the slight (average 0.9 °C) increases in maximum daily air temperatures in YP relative to MM in the final years of this study suggest that changes in AAR may become more pronounced once only coarse canopy material remains. From 2010 on, after most of the needles had been lost, Tsph and albedo (indicators of stand interception capacity and snow conditions) explained 46% of the within-stand variance in 1 April SWE while canopy transmittance and albedo (indicators of energy available for melt) explained 31% of the variance in AAR.

Pugh and Small (2011) found that snow accumulation did not change until trees had reached the grey phase. However, they did find that ablation rates were accelerated in the red relative to the green stand, and snowpack was depleted earlier as a result of increased needle litter reducing snow albedo. At the much lower elevation Mayson Lake sites (1270 m *vs* ~2700 m), where April 1 SWE averaged 208 mm over the 7-year study period compared to the much higher 25-year average of 355 mm in Colorado (Pugh and Small, 2011), snow processes only changed at the red attack phase in association with substantial needle loss that occurred in year four (2009). This was also the year that the attacked stand was more similar to the CC than the mature mixed stand: April 1 SWE in the attacked stand was most similar to that in CC, and AAR was most different from that in MM than any other year.

In Colorado, snowpack depletion occurred one week earlier in the red stand as a result of increased litter, reduced albedo and more rapid ablation. Maximum litter cover at the Colorado sites was 20% compared to 61% at Mayson Lake, both measured during the red phase of attack. Pugh and Small (2011) estimated that at 20% litter cover, snow surface albedo would be reduced by 25%. Based on the albedo decay curve derived from measurements at Mayson Lake (Figure 8), albedo was reduced by up to 35% at 20% pine litter cover. Other than in 2009, however, the effects of canopy loss and litter production on AAR at Mayson Lake were largely overwhelmed by weather. In the final years of the study, differences in AAR between YP and MM were influenced by increased albedo in YP as a result of minimal litter availability in the grey stand, while litter continued to fall in MM thus affecting albedo and ablation in that stand.

Pugh and Small (2011) found that snowpack depletion advanced by one week in both red and grey stands relative to green stands, which was interpreted to result from a combination of decreased albedo in the red and increased transmittance in the grey stands. However, while these variables were important in driving relative dates of snow disappearance at Mayson Lake, this date was most affected by the weather, which was assumed to play only a minor role in the Colorado study. The major effects of weather were also noted by Boon (2012), who found that in a high snow year in northern interior BC the interception capacities of both green mixed species and grey pine canopies were exceeded more frequently, thus reducing SWE differences between forested and open sites.

These results consistently indicate that a measurable hydrologic response to MPB infestation and beetle kill may not occur for a number of years post-attack and will depend on the location, the type of stand affected, and weather. The largest change in snow ablation appears to occur during the year of highest needle loss, whereas snow interception begins to decrease in the years after needle loss. Compensating effects such as increased albedo in the attacked stand relative to a green stand, continued interception effectiveness of grey trees, increased below canopy wind speed and changes in the balance of short- and long-wave radiation as the canopy opens, and inter-annual variability in weather all affect snow accumulation and melt in the attacked stand. Further, the effects of other tree species, regeneration, and growth of trees in the understory will also moderate the effects of main canopy die-off.

This study provides new information for use in watershed assessment, salvage harvest planning, and modelling (e.g. Rutter *et al*., 2009) in areas with moderate snowfall and with young, mixed, and multilayered stands subject to natural disturbance such as MPB. The results of this study highlight the complexity of relationships between meteorological conditions, stand attributes, and snow that complicate the prediction of changes in SWE and AAR with changing stand condition as well as the need for longer term research. Re-measurement of both stand and snow variables beyond early grey attack is key to understanding the changing importance of specific ecohydrologic processes (i.e. needle loss, the presence of coniferous understory) over the longer term. Quantification of stand-scale snow response to MPB across a broader range of physiographic settings is also necessary in order to extrapolate results to new locations and to the watershed scale for modelling of associated changes in streamflow.

CONCLUSIONS

This study quantified the effects of MPB-induced canopy changes on snow cover dynamics over a 7-year period in a young pine (YP) and a mature mixed species (MM) stand relative to a clearcut (CC). MPB attack in 2005 resulted in a gradual forest cover change at Mayson Lake, with almost complete defoliation of pine in YP 6 years later. Average canopy transmittance in YP increased by >20% as trees turned from green to grey. Loss of pine from the main canopy in MM did not affect canopy transmittance due to the high density of other species and a well-developed understory (intermediate and suppressed tree) layer. The greatest increase in canopy transmittance and litter production in YP occurred 4 years post-MPB attack. Increased litter production resulted in a significant non-linear decrease in snow surface albedo. This effect was short-lived; by the following year when trees in YP were grey, snow surface albedo was higher than in MM.

Forest cover change reduced both SWE and AAR in YP and MM relative to the CC in all years, the largest effect occurring in the year of least snowfall. SWE was significantly higher in YP than in MM in all but the 2 years of average snowfall. The difference in SWE between these stands increased with needle loss in YP due to a decrease in snow interception. AARs were also significantly higher in YP than MM in all years except the year of least snowfall and with the shortest melt season.

Inter-annual variability in weather largely overwhelmed the effects of changes in the canopy. The largest differences in April 1 SWE between YP and MM occurred once most trees in YP had turned grey. AAR did not appear to increase relative to either CC or MM over the study period likely a result of the compensating effects of increased snow surface albedo in YP relative to MM post needle loss and a change in the balance of short- and long-wave radiation as the YP canopy thinned.

The results of this study suggest that changes in snow-dominated hydrologic response following MPB may be gradual in areas of moderate snowfall such as Mayson Lake, rather than the definitive changes noted in other higher elevation studies, and will be affected by stand type. Continuing work will clarify whether the effects of MPB-related canopy loss are greater during average snow years, as fine woody material is lost from the main canopy and as stems blow down, as well as the effects of growth of the remaining trees and regeneration.

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