Forest disturbance effects on snow and water yield in interior British Columbia

Rita Winkler, Dave Spittlehouse, Sarah Boon and Barbara Zimonick

ABSTRACT

Long-term studies at Mayson Lake (ML) and Upper Penticton Creek (UPC) in British Columbia's southern interior quantify snow-dominated hydrologic response to natural disturbances and logging. Following natural disturbance at ML, changes in snow accumulation related directly to mountain pine beetle attack were measurable by the fifth year following attack, when canopy transmittance had increased 24% due to needlefall. In year 1, April 1 snow water equivalent (SWE) was 48% higher in the clearcut than in the pine forest. This difference was reduced to 23% by year 8. A 3-year lag in snow response was also observed in a nearby burned stand where SWE was on average 27 and 59% higher in the clearcut than in the burn and forest, respectively. At UPC, April 1 SWE averaged 12% more and 12% less in a low and high elevation clearcut than forest, respectively, and snow disappeared ~10 days earlier in both clearcuts. Partially as a result of snowmelt synchronization from higher with lower elevations after 50% of the treatment watersheds had been clearcut, April water yield increased and June to July yield decreased. Research results improve evaluation of hydrologic response to forest disturbance, including retention of beetle-killed stands versus salvage logging.

Key words | forests, logging, natural disturbance, snow accumulation and ablation, water yield

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INTRODUCTION

Streamflow from most watersheds in southern interior British Columbia (BC) is generated by mid to high elevation spring snowmelt. Most of this region is forested with lodgepole pine (*Pinus contorta* Dougl.), Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt). These forests comprise much of the timber harvesting landbase and are also affected by insects, disease and wildfire. Since 1994, 17.5 million ha of lodgepole pine-dominated forest in BC have been attacked by mountain pine beetle (MPB) and large areas have been salvage harvested. Future forest disturbance – including wildfire frequency and severity (Westerling *et al.* 2003; Gillett *et al.* 2004) and attack by insects and pathogens (Fettig *et al.* 2013) – is expected to increase under climate change, further affecting forest cover. Extensive changes in forest canopy structure raise concerns regarding the effects on snow accumulation and ablation, and the potential for associated changes in snowmelt-generated streamflow volume and timing.

Coniferous forest canopy attributes are well-correlated with snow accumulation and ablation (Varhola *et al.* 2010); these interrelationships vary with forest structure and condition, weather, elevation and aspect (Ellis *et al.* 2011). Following forest disturbance and regrowth, changes in snow accumulation relate largely to shifts in canopy interception capacity and subsequent sublimation of that intercepted snow. Changes in ablation rates are predominantly a result of shifts in the short- and long-wave energy balance at the snow surface as mediated by canopy cover (Boon 2009; Varhola *et al.* 2010). Depending on location, year and forest structure, April 1 SWE and snow ablation rates in the BC interior increased by 5–70 and 30–100%, respectively, following clearcut logging (Toews & Gluns 1986; Winkler *et al.* 2005; Winkler *et al.* 2010); increases comparable to those reported by others (Golding & Swanson

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1986; Troendle *et al.* 1988; Pomeroy *et al.* 2002). Following the loss of mature forest canopy due to insect attack in BC and Colorado, peak snow water equivalent (SWE) increased by 11–21% and the date of snowpack depletion advanced by up to 1 week (Bewley *et al.* 2010; Pugh & Small 2012; Winkler *et al.* 2014). SWE increased by 11%, ablation rates almost doubled and snow disappeared 23 days earlier in a burned relative to an unburned forest in Oregon (Gleason *et al.* 2013) while in southwestern Montana, SWE and snow ablation rates increased by up to 10% and 57%, respectively, following wildfire (Skidmore *et al.* 1994).

Increased snow accumulation and ablation rates following loss of forest cover generally result in higher peak spring streamflows and higher annual flows; however, the magnitude of change varies widely (Stednick 1996; Moore & Wondzell 2005). For example, in Colorado and Wyoming, post-MPB annual water yield response varied from increases of 30% to reductions of 20%, depending on whether beetle-killed forests were even-aged without significant understorey, or mixed species with significant non-pine understorey (Stednick & Jensen 2007). Changes in spring streamflow following a severe wildfire in central BC were found to be minor; however, annual peak flow timing was advanced by approximately 2 weeks (Owens *et al.* 2013). A comparison of four snow-dominated watersheds in BC and Colorado (Green & Alila 2012) found that, once 33–40% of a watershed had been clearcut, the magnitude of peak flows of a given frequency increased over the full range of return periods studied. The frequency of peak flows of a given magnitude increased by at least two to three times, depending upon watershed characteristics such as size, elevation, aspect and gradient.

Although the interrelationships between forest structure, snow processes and water yield are well-understood in general, few field studies have linked stand- to watershed-scale hydrologic response to forest disturbance in snow-dominated watersheds in BC. Modelling studies that have attempted to do this are limited by the scarcity of post-disturbance field data.

Long-term stand- and watershed-scale research at Mayson Lake (ML) and Upper Penticton Creek (UPC) focuses on post-disturbance hydrologic response in forested watersheds typical of southern interior BC. Detailed results of specific projects at each of these locations have been published or are in preparation (Winkler *et al.* 2005, 2014; Winkler & Moore 2006; Green & Alila 2012; Schnorbus & Alila 2013). This paper links results from each of these two research programmes to quantify: (1) the relative effects of natural disturbance and clearcut logging on snow processes; and (2) water yield response to changes in snow processes with clearcut logging, the common forest management response to natural disturbance. This study is the first to discern such linkages at the small watershed scale in southern interior BC based on long-term field research. Results provide operationally relevant information required for forest planners and hydrologists to assess the potential consequences of a range of forest management options on water supplies, including the effects of clearcut salvage logging following natural disturbance.

STUDY AREA AND METHODS

Study sites

Long-term hydrologic research in southern interior BC is centred at ML and UPC (Figure 1). The ML study area includes sites with forest cover varying from clearcut, to new regeneration, young and mature forest and burned forest. Research at these sites began in 1995 and focuses on stand-scale hydrologic response to forest cover loss and regrowth. The UPC study area includes the three small watersheds of 240, 241 and 242 Creeks in which streamflow was gauged prior to, during and post-logging. Research at UPC began in 1985 and projects have focused on water quantity and quality, aquatic ecology, channel morphology, stand-scale water balance and groundwater. The long-term datasets from UPC are also used in hydrologic and climate change modelling.

Mayson Lake

ML is approximately 50 km northwest of Kamloops (51°13′N 120°24′W, 1,270 m asl) in the Montane Spruce biogeoclimatic zone (BC FLNRO 2008). Annual average precipitation is 560 mm, of which ~45% falls as snow and the mean annual air temperature is 2.7 °C (Table 1).

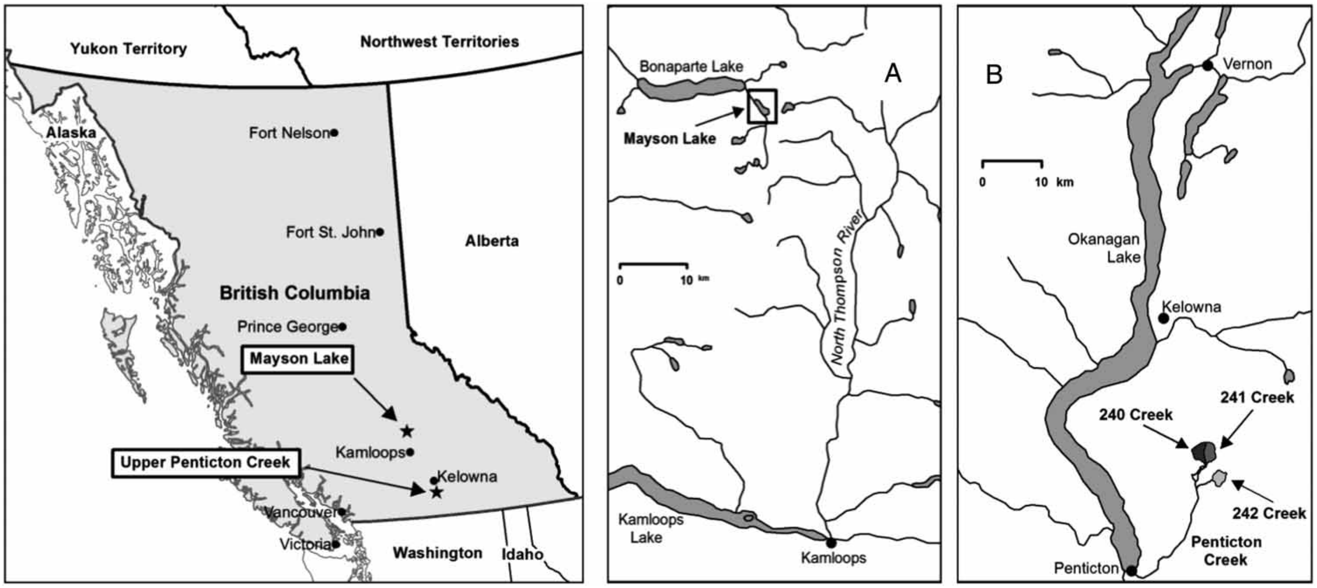

Figure 1 | Location of the Mayson Lake research site (A) and Upper Penticton Creek watershed experiment (B).

Table 1 | Study location, design and general characteristics (adapted from Redding *et al*. 2010)

	Mayson Lake	**Upper Penticton Creek**
Study duration	1995–present	1985–present
Study type	Stand-scale process studies	Paired watershed; before-after-control-impact design
Control watershed or plot area	Clearcut; 0.5 ha	240 Creek; 500 ha
Treatment watershed or plot area	MM forest; Young pine (YP) (various); Burned forest; 0.5 ha each	241 and 242 Creeks; 500 ha each
Pre-treatment measurement period	NA	1986–1995
Treatments	Forest regrowth, wildfire, MPB	Clearcut logging in 241 and 242 Creeks
Post-treatment measurement period	3–11 years	Ongoing
Location (general)	Thompson Plateau	Okanagan Plateau
Location	51°13′N 120°24′W	49°39′N 119°24′W
Biogeoclimatic zone	Montane spruce	Engelmann spruce
Elevation range	1,260–1,300 m	1,600–2,140 m
Total area	2 km^2	15 km^2
Precipitation (mean annual)	560 mm	750 mm
Temperature (mean annual)	2.7 °C	1.9 °C
Temperature January (mean minimum)	−11.7 °C	−10.5 °C
Temperature July (mean maximum)	22.4 °C	19.5 °C

All sites at ML are located on gently rolling terrain within 5 km of each other. The five sites discussed here represent forest cover typical of the region: young (~35 years old in 2006) lodgepole pine (YP) which at this site had been thinned and pruned; mature mixed (MM) Engelmann spruce, subalpine fir and lodgepole pine (MM); and a recent clearcut (CC) (Winkler *et al.* 2005) as well as a forest similar to MM burned in 2003 and a clearcut near the burn. Lodgepole pine is the dominant trees species at ML comprising 99 and 55% of the main canopy at YP and MM, respectively. Although the understorey in YP was also dominated by pine, trees in this layer at MM were predominantly Engelmann spruce and subalpine fir. As a result, pine comprised 78% of the total stems in YP and only 17% in MM. Most lodgepole pine trees >14 cm in diameter at the study sites – and throughout the region – were attacked by MPB in 2005. In 2006, the main canopy of YP was 12.7 m tall, evenly spaced (1,000 stems per hectare (sph): basal area 18 m^2 ha^{-1}) with a canopy transmittance of 27%, as measured using hemispherical photographs (Winkler *et al.* 2014). In contrast, MM was denser (3,631 sph; canopy transmittance 18%) with 93% of the stems forming the 6-m tall, predominantly non-pine understorey; trees forming the main canopy were much larger (23.4 m tall; basal area 50 m^2 ha^{-1}). During the period 2006–2012, 58% of the pine trees forming the main canopy in YP and 20% in MM lost all needles and fine canopy material. Canopy transmittance to the snow surface in spring increased to 48% in YP by the end of the study but remained at 18% in MM, as a result of the dense understorey. A detailed description of these sites can be found in Winkler *et al.* (2014).

The burned stand and nearby clearcut were located approximately 4 km east of YP. Prior to burning in 2003, this stand was similar to MM but stand inventory information was not available. All trees were killed during the fire and the charred stems remained standing. Canopy transmittance in the burn was 77% in 2004 and increased to 83% by the fall of 2007.

Upper Penticton Creek

UPC is 26 km northeast of Penticton (49°39′N 119°24′W, 1,600–2,140 m asl) in the Engelmann spruce–subalpine fir biogeoclimatic zone. Average annual precipitation is 750 mm, of which ~45% falls as snow and the mean annual air temperature is 1.9 °C (Table 1).

Hydrologic monitoring at UPC began in 1985 in three separate watersheds (240, 241 and 242 Creeks). Each watershed is ~5 km^2 in size with gentle to steeply sloping terrain; the 240 and 241 Creek watersheds have a southerly and the 242 Creek watershed a westerly orientation. The elevation range of the 240 and 241 Creek watersheds is ~1,600–2,000 m and of the 242 Creek watershed is ~1,700–2,140 m. The area is underlain by coarse-grained granitic rock covered by glacial till and overlain by glacio-fluvial sand and gravel in the lower reaches. Soils are coarse sandy-loam over loamy-sands, low in clay and high in coarse fragments, have a low water holding capacity and are well drained. Forest cover is predominantly lodgepole pine in the 240 and 241 Creek watersheds, with mixed stands of Engelmann spruce, subalpine fir and lodgepole pine in the 242 Creek watershed. Mature trees are >120 years old and up to 26 m tall.

The UPC experiment follows a paired watershed before-after control-impact design. The control period was 1985–1995 and logging began in the winter of 1995 in both the 241 and 242 Creek watersheds. The watersheds were clearcut incrementally, with intervening monitoring periods lasting 3–5 years. After final logging in 2000 and 2007, 50% of both the 242 and 241 Creek watersheds had been clearcut, respectively; the 240 Creek watershed remained an uncut control. Areas logged were fairly continuous across the lower half of both the 241 and 242 Creek watersheds and approximately 65 hectares in the upper 241 Creek watershed were also logged in a continuous clearcut. Changes in water yield following 50% clearcut logging are discussed here because this represents the extensive salvage response to natural disturbance common throughout the BC southern interior.

Data collection and analysis

At ML and UPC, weather data were collected in both clearcut and forested sites. Variables included incident and reflected shortwave radiation (LiCor LI200; Eppley B&W pyranometer), air temperature and humidity at 2 m (Vaisala HMP35C), wind speed at 3 m (MetOne 013 cup anemometer; RM Young wind monitor), snowpack temperature at 0, 0.2 and 0.5 m depth (Type K thermocouples), snow surface temperature (Apogee infrared radiometer), snow depth (Campbell Scientific Inc. SR50A) and rainfall (tipping buckets; plus standpipe gauge at UPC). Data were recorded on Campbell Scientific Inc. CR10X and CR1000 data loggers scanning every minute and providing hourly and daily summaries. Canopy transmittance for sites at ML, as determined from hemispherical photographs detailed in Winkler *et al.* (2014), is included here with additional results from 2013 at both ML and UPC.

SWE was measured at 32 stations arranged in a 10–15 m-spaced grid at each site at ML (YP, MM, CC, a burn and a clearcut near the burn), and in a low (1,600 m) and high (1,950 m) elevation clearcut/forest site pair at UPC. Measurements were made within a 1 m radius of each station marker using a standard Federal snow tube. Maximum errors associated with these measurements are within the 7–12% range typical of the Federal sampler for SWEs at both ML and UPC, as outlined in Winkler *et al.* (2005). Surveys began on March 1, were repeated on or near April 1, and then continued weekly to biweekly through the melt season. Post-MPB attack SWE was measured at ML from 2006 to the present (Winkler *et al.* 2014); these data are complemented by surveys completed in the same stands prior to attack in 2003–2005. Snow surveys were completed in the burn and nearby clearcut from 2004 to 2008 (Winkler 2011). Snow surveys at the low and high elevation sites at UPC began in 1995 and 2000, respectively, and have continued to the present. The original low elevation clearcut site was replaced by a new clearcut in 2005 because of the potential confounding effects of forest regrowth. Both clearcuts were surveyed for 2 years and differences in SWE and ablation were not significant. Ablation rates were calculated using the SWE on the survey date prior to continuous melt and the number of days between that and the snowpack depletion date. The date of snow depletion was calculated using the average ablation rate measured between the final two sampling dates with snow cover. Ratios of snow in the forest relative to a clearcut standardize comparisons across multiple studies. UPC SWE data from 2008 to 2011 (post-treatment in the 241 Creek watershed) were smoothed using the lowess technique to illustrate differences between sites.

Daily streamflow at UPC was measured by the Water Survey of Canada (http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=4EED50F1-1) using H-flumes, fitted with V-notch inserts during low flow, and Stevens A-71 type continuous water level recorders at the outlet of each watershed. Complete datasets are available for all three watersheds from 1986 to 2011. Water yield was summarized as annual and April to July monthly yield for periods prior to logging (1986–1995) and after 50% of the treatment watersheds had been clearcut logged (2007–2011 and 2001–2011 for 241 and 242 Creeks, respectively).

Pre-logging relationships between water yield from the control and treatment watersheds were used to predict post-logging yield at UPC when the coefficients of determination for these relationships were >0.80 ($p < 0.01$). Predicted yield was compared to actual flows to determine the magnitude of change. ANOVA was used to test whether changes in water yield were statistically significant. Data summaries and statistical analyses were completed using SYSTAT 11, with statistical significance for all tests set to $\alpha = 0.05$. Differences in daily flows pre- and post-disturbance were graphed to show shifts in flow timing.

RESULTS AND DISCUSSION

At ML and UPC, precipitation falls mainly as snow from late October until mid-April or mid-May, respectively. By April 1, SWE in the open is 200–250 mm at ML, and 250–350 mm at UPC. The snowpack at ML is usually depleted by mid-May, and by early June at UPC. At both locations, average daily air temperature increases from $-7\,^{\circ}$C in January to $+5\,^{\circ}$C during the melt period. Average daily wind speed (2 m s^{-1}) varies by <10% between years, while daily maxima reach 8–12 m s^{-1} during the melt period. Solar radiation during melt averages 17.2 MJ m^{-2} d^{-1} at ML and 19.5 MJ m^{-2} d^{-1}at UPC, where melt occurs a month later than at ML.

At UPC, annual water yield from 240, 241 and 242 Creeks ranges from 0.8 to 3 million m^3 yr^{-1} (160–600 mm; average 380 mm), or 30–60% of total annual precipitation. The highest daily flows occur in May during mid and high elevation snowmelt, reaching up to 1.5 m^3 s^{-1}. Average pre-disturbance water yields are provided in Table 2.

Table 2 | Average (standard deviation, SD) changes in water yield generated following clearcut logging of 50% of the area in each of the 241 and 242 Creek watersheds, for months when pre-disturbance water yield was well correlated between the control and treatment watersheds ($r^2 > 0.80$, $p < 0.01$).

	Pre-disturbance average (SD) water yield (mm)			**Post-disturbance average (SD) per cent difference from predicted**	
	240 Cr	**241 Cr**	**242 Cr**	**241 Cr**	**242 Cr**
Per cent logged	0	0	0	50	50
Years of survey (*n*)	10	10	10	4	11
Total annual water yield	336 (109)	356 (107)	387 (107)	6 (5)	11 (19)
Monthly water yield:					
April	23 (19)	40 (29)	18 (13)	34 (52)	125 (119)
May	161 (36)	178 (53)	150 (31)	36 (23)	
June	86 (69)	80 (66)	133 (88)	– 28 (7)	– 16 (13)
July	28 (21)	25 (24)	38 (29)	– 1 (42)	– 22 (14)

Changes shown are the difference between measured flows in the logged watershed and flows predicted using the pre-disturbance relationships between the treatment and control, 240 Creek (shading indicates $p < 0.05$).

Changes in snow following natural disturbance at ML

As detailed in Winkler *et al.* (2014), canopy condition following the 2005 MPB attack at ML changed gradually from full, green canopy cover (survey period A; 2003–2006) to red with most canopy material retained (survey period B; 2007–2010), to grey with loss of considerable canopy material (survey period C; 2011–2014). Canopy transmittance measured from 2007 to 2013 increased from 27% to 51% (Figure 2). This gradual change in the forest canopy resulted in an equally gradual change in snow accumulation and ablation over the 12-year survey period (Figure 3).

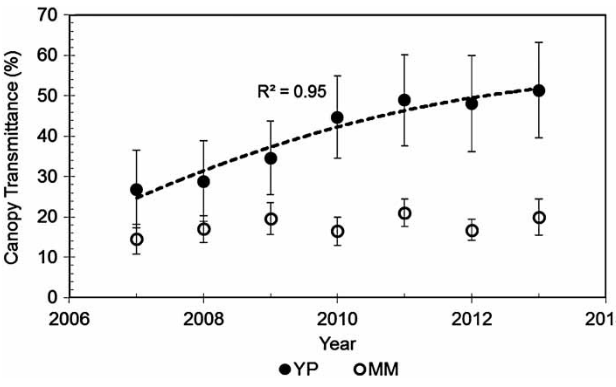

Figure 2 | Annual canopy transmittance in a young pine (YP – solid circles) and mature mixed species (MM – open circles) stand at Mayson Lake (adapted from Winkler *et al.* 2014). Error bars indicate 1 SD. Transmittance was measured in late spring each year, beginning 2 years after MPB attack.

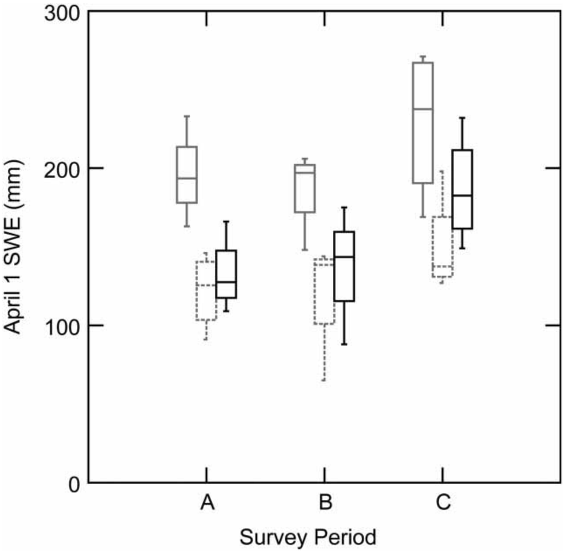

Figure 3 | April 1 SWE (mm) in the clearcut (CC – grey, solid), mature mixed species stand (MM – grey, dotted) and young pine stand (YP – black, solid) at Mayson Lake. During survey period A, pine tree canopies were green (2003–2006); in period B, following MPB attack, pine tree needles were red (2007–2010) and during period C, the pine canopy had lost needles and fine braches and was grey (2011–2014).

April 1 SWE averaged 56% higher in CC than MM, with the difference between these sites decreasing slightly (from 61 to 53%) over the study period as needles were lost from the pine trees in the main canopy of MM. Differences in April 1 SWE between CC and YP decreased from on average 48% during survey period A, to 36% during period B and 23% in period C (Figure 3). Canopy loss also affected differences in April 1 SWE in YP relative to MM: the difference increasing from 8% in survey period A, to 13% in period B and 24% in period C. Changes in the ratio of forest to clearcut April 1 SWE are shown in Figure 4. Pugh & Small (2012) also observed changes in snow accumulation only once the trees had reached the 'grey' phase. The greatest difference between the forested sites and CC (68 and 128% more in CC than in YP and MM, respectively) occurred in 2010, the year of lowest snowfall when both canopies were effective at intercepting a larger proportion of the total snowfall. Larger differences in forest versus open SWE during low snow years have also been reported by others (Hedstrom & Pomeroy 1998; Jost *et al.* 2007; Boon 2012). These results suggest a considerable lag between insect attack and snow response until most fine canopy material has been lost and that clearcutting pine shortly after attack may result in a greater immediate hydrologic response than would be observed without logging.

Ablation rates were most influenced by inter-annual variability in the weather; however, differences between both forests and the clearcut were significant in all years (Winkler *et al.* 2014). On average, ablation rates were 1.2 and 1.8 times higher in CC than YP and MM, respectively. Prior to MPB attack, snow disappeared a maximum of 6 days earlier in YP than in CC, as a result of reduced SWE and differences in the energy balance as described by others (Pomeroy *et al.* 2009; Pugh & Small 2012). From 2011 on, snow disappeared from both sites at the same time, whereas snow disappeared from MM ~5 to 10 days later than in CC.

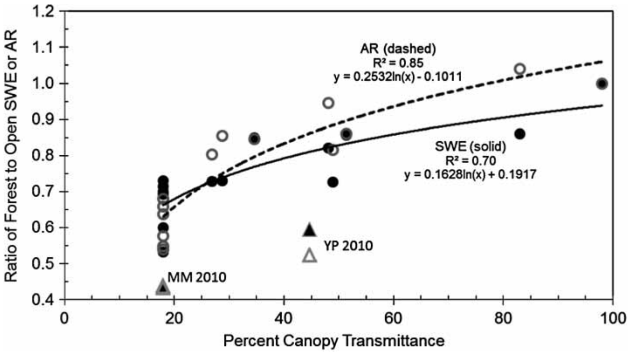

Figure 4 | Ratios of forest and burn to clearcut April 1 SWE (SWE – solid circles) and ablation rate (AR – open circles) with per cent canopy transmittance at Mayson Lake from 2007 to 2013. The extremely low snow year 2010 (triangles) for the young pine and mature mixed stands, when both forest canopies had a much larger effect on snow than in all other years, is not included in the regression lines.

At the burned site, where pre-disturbance forest cover was similar to MM (transmittance 18%), canopy transmittance was 87% in the fourth year after the fire. In the first year post-fire, April 1 SWE in the burn was similar to that in the forest and 36% lower than that in the nearby clearcut. Differences in April 1 SWE between the burn and forest averaged 59% and were highest in post-fire years 3 and 4 (77% and 63%, respectively). Average ratios of April 1 SWE in the burn relative to the clearcut and burn to forest were 0.72 and 0.62, respectively. Average ablation rates were higher (31–93%) in the burn than in the forest in all post-fire years; however, the largest difference was measured in year 5. Ablation rate ratios of burn relative to clearcut and burn to forest in year 5 were 1.2 and 0.62, respectively (Winkler 2011). This corresponds with results from southwestern Alberta, where Burles & Boon (2011) found that maximum SWE increased >50% 6 years following severe wildfire, and that the snowmelt period was shortened by 9–15 days as a result of a ~30% increase in shortwave radiation and sensible heat fluxes. These results suggest that, similar to insect attack-related defoliation, snow accumulation and melt response to forest cover loss following a wildfire may be delayed until needles and fine canopy material are lost and burned stems topple.

The relationships between forest to clearcut ratios of April 1 SWE or ablation rates for each survey year and increasing canopy transmittance post-MPB attack at ML are shown in Figure 4. With the exception of 2010 (lowest snowfall), canopy transmittance explained 70% or more of the variability in both ratios. This result is similar to previous work, where green forests (4–23 m tree heights) showed a 6% reduction in April 1 SWE for every 10% increase in crown closure (Winkler & Roach 2005). Figure 4 also highlights the influence of inter-annual weather variability, particularly in MM where canopy transmittance remained constant at 18%.

Changes in snow accumulation and ablation following clearcut logging at UPC

At UPC, long-term (1995–2012) April 1 SWE averaged 328 mm (SD = 88 mm) in the flat, low elevation clearcut, 12% (range 0–38%) more than in the adjacent lodgepole pine forest (average 292 mm (SD = 64 mm)). In the large, south facing, high elevation clearcut, April 1 SWE (2000–2012) averaged 318 mm (SD = 91 mm), 12% (range −12 to +9%) less than the adjacent forest, where SWE averaged 363 mm (SD = 91 mm). Ratios of SWE in the forest relative to the clearcut at low and high elevation averaged 0.89 and 1.14, respectively. Ablation rates averaged 8.9 mm d^{-1} (SD = 4.5 mm d^{-1}) and 7.3 mm d^{-1} (SD = 3.2 mm d^{-1}) in the low elevation clearcut and forest, respectively (ratio of forest to clearcut 0.82). At high elevation, ablation rates were similar in the clearcut and forest, averaging 9.2 mm d^{-1} (SD = 4.8 and 4.4 mm d^{-1}, respectively). The snowpack completely disappeared ~10 days earlier on average in the clearcut than in the forest at both low and high elevations. In 2010 (lowest snow year), snow in the high elevation clearcut disappeared 23 days earlier than in the forest. This was also the year of the highest post-treatment peak flow event. These differences are smaller than those observed at ML due to differences in forest structure: single canopy layer pine at UPC (canopy transmittance 26%, average tree height 15 m) compared with multi-layered Engelmann spruce, subalpine fir and pine in MM at ML (canopy transmittance 18%, average tree height 23 m).

Figure 5 clearly illustrates the advancement in the timing of melt runoff from the high elevation clearcut to coincide with that from lower elevations. It also shows that the upper elevation forest continues to accumulate snow after melt commences in the clearcut. Figure 5 demonstrates that snow losses occur in the clearcut during winter, partially depleting the snowpack prior to the main melt season. Other research suggests that winds >5 m s^{-1} can redistribute snow scoured from the centre of clearcuts into the forest and also deplete clearcut snowpack via enhanced sublimation (Varhola *et al.* 2010). However, snow survey transects measured for a 3-year period across the upper elevation clearcut and into the forest (data not shown) showed no redistribution of snow from the clearcut into the forest to account for our results. Similarly, increased snow deposition was not measured beyond two tree heights into the forest around a 10 ha clearcut near Sicamous, also in south central BC (Spittlehouse *et al.* 2004).

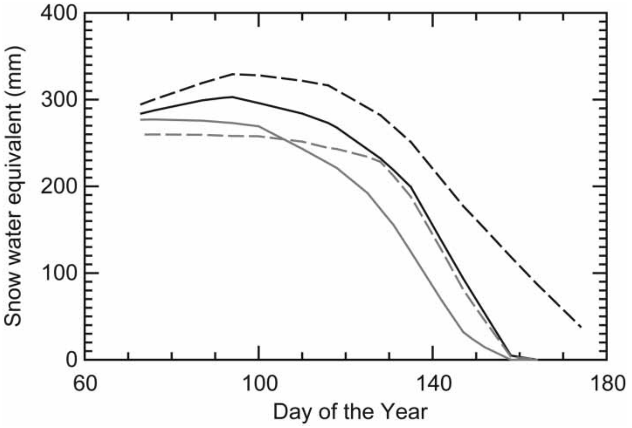

Figure 5 | March to June trend in SWE for 2008 to 2011 in a low elevation clearcut (grey, solid) and forest (grey, dashed), and in a high elevation clearcut (black, solid) and forest (black, dashed) at UPC. Lines were generated using lowess smoothing of 32 points per site measured bi-weekly each year.

The south-facing upper elevation clearcut and forest receive ~6% more solar radiation than the flat, low elevation sites during the April to June period, when the snowpack ripens and melts. Canopy transmittance during this period is 26% for the low and 25% for the high elevation forests. Throughout the pre- and main-melt periods, maximum daily air temperature decreases by, on average, −1.4 °C 100 m^{-1} between low and high elevation in both the clearcut and forest. In contrast, minimum daily air temperature increases between low and high elevation, by +0.6 °C 100 m^{-1} in the clearcut and by +0.4 °C 100 m^{-1} in the forest. This is a result of the night-time drainage of cold air from upper elevations and ponding on the flatter lower sites. Wind speeds are similar at the upper and lower sites. These data indicate that differences in the late winter energy balance between lower and upper sites result in the SWE depletion patterns shown in Figure 5.

Changes in water yield following clearcut logging at UPC

During the pre-logging period (1986–1995), average snowmelt-generated water yields in 240 Creek (control) were well-correlated with 241 and 242 Creeks for total annual yield and April, June and July monthly yield ($r^2 > 0.80$; $p < 0.01$). May water yield in 240 Creek was also well-correlated with yield in 241 Creek, but not with 242 Creek. This is likely due to differences in snowmelt timing as a result of differences in the aspect, elevation range, soil and drainage characteristics of the 242 Creek watershed.

Post-logging water yield (1996–2011 average) was compared to that predicted using the pre-logging relationships.

The differences are shown in Table 2. In 241 Creek, total annual water yield increased slightly (6%) post-logging, however, no significant change was observed in 242 Creek. In 242 Creek, April water yield increased by >100% over predicted values. In 241 Creek, May water yield increased by 36% over predictions. June water yields decreased by 28 and 16% relative to predicted in 241 and 242 Creeks, respectively. July water yields were also reduced (22%) in 242 Creek. Differences between predicted and actual yield for other periods were not significant.

Changes in average daily post-logging spring streamflow regime in 241 and 242 Creeks relative to 240 Creek (control) are shown in Figure 6. Peak streamflows at UPC generally occur in the first half of May, at which time snow in the 241 Creek upper elevation clearcut has, on average, been depleted by ~50%. We hypothesize that this rapid loss

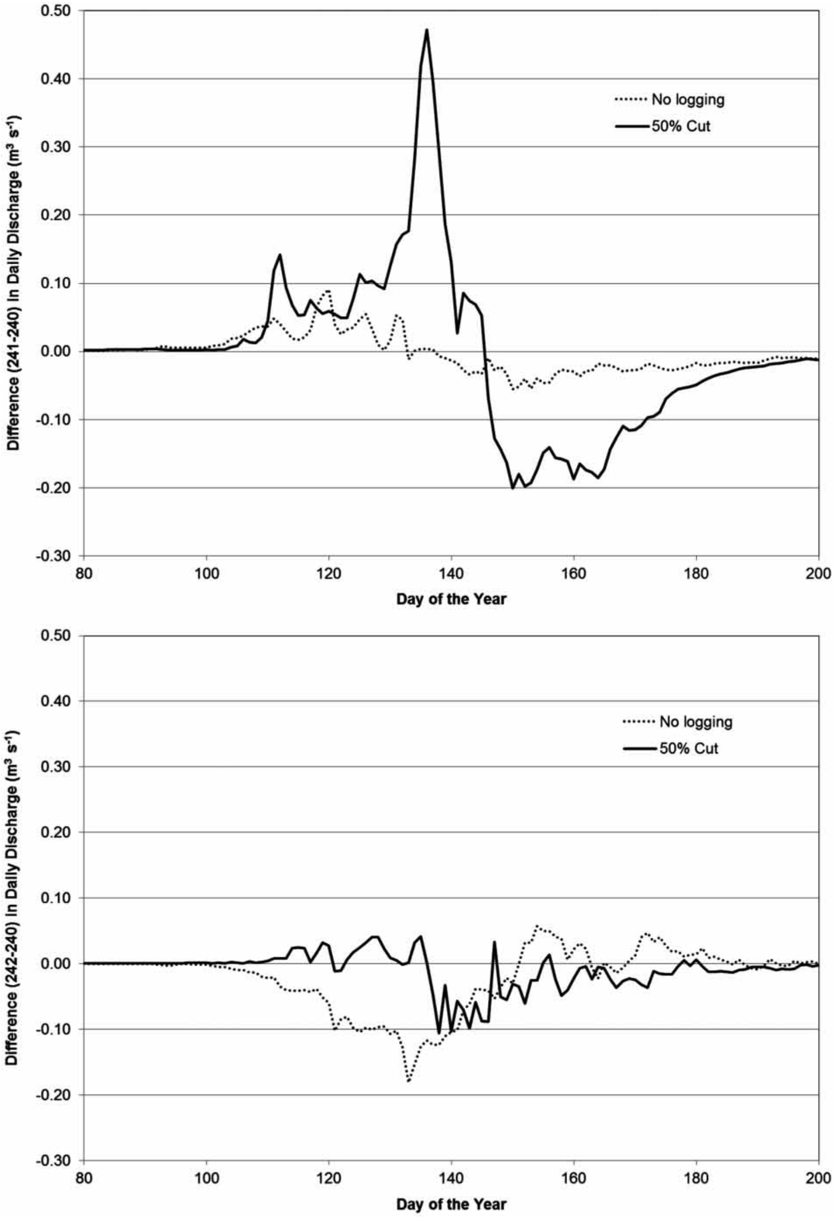

Figure 6 | Difference in average daily discharge between 240 and 241 Creeks (top) and 240 and 242 Creeks (bottom) prior to logging (grey dotted line – 1986–1995) and post 50% clearcut (black solid line – 2008–2011 for 241 Creek and 2001–2011 for 242 Creek).

synchronizes melt runoff from the high elevation openings with that from lower elevations, contributing to the increased early spring streamflow magnitudes observed in 241 Creek post-treatment relative to 240 Creek (Figure 6). In a recent modelling study of changes in peak flow with clearcut logging at UPC, Schnorbus & Alila (2013) suggest the same mechanism to explain significant increases. Melt in the high elevation forest likely contributes to the increased difference in discharge around May 20 (day 140). After this date, insufficient snow remains to offset early-season losses, thus discharge in June and July is reduced relative to the control. High elevation snow data are not available in the 242 Creek watershed so a similar comparison cannot be made there.

Previous studies have reported similar changes in streamflow from snow-dominated watersheds following clearcutting of >30% of the watershed (Stednick 1996; Moore & Wondzell 2005; Green & Alila 2012). At Camp Creek, in the Okanagan Basin, April water yield increased significantly, and the timing of peak flow was significantly advanced relative to the control (Moore & Scott 2005). Using field data and model-derived datasets for three locations in BC and Colorado, Green & Alila (2012) found an 11–35% increase in peak flows once 33–40% of the watersheds had been clearcut, with the timing of peak flows advanced by up to 1 week as a result of synchronization of melt from upper and lower elevations.

Pomeroy *et al.* (2012) simulated the relative effects of MPB, fire and salvage logging on hydrologic response in the Marmot Creek watershed, in Alberta's Rocky Mountains (9.4 km^2, 1,600–2,825 m elevation). As was observed at UPC, they also predicted a stronger response in spring daily peak flows than in seasonal water yield. Increases in total spring plus summer water yield were <10% for all scenarios. The largest increases in daily peak flows (20–23%) were predicted when burned stands were salvage logged over 60% of the watershed area or if forest cover over the entire watershed was removed, respectively. In the large Baker Creek watershed in central BC (1,570 km^2), Zhang & Wei (2012) found that mean annual flow increased by 48% following extensive MPB attack and salvage logging over 62% of the total watershed area, and that the effects of such widespread forest disturbance overrode the compensating effects of climatic variability observed in less disturbed watersheds. Results at ML suggest that, without salvage logging, streamflow response would be mitigated by non-pine trees, well-developed understorey and standing dead trees, as well as delayed for some years until most canopy material was lost.

It is also important to note that forest disturbance-driven shifts in snowmelt-generated runoff may become more pronounced with climate change. Davis (2012) applied climate change scenarios to UPC using the Cold Regions Hydrological Model (Pomeroy *et al.* 2007). Results indicated that snow accumulation will likely be reduced at low elevations and snow duration will decrease at high elevations. The frequency of mid-winter melt events is likely to increase, particularly in disturbed forest stands. Snow accumulation and ablation sensitivity to climate change will increase with increasing forest disturbance severity, with greatest sensitivity at lower elevations. The combined effects of forest disturbance and climate change on snowmelt regimes increases the likelihood of flood risk in spring and prolonged low flow seasons.

CONCLUSIONS

Research at ML and UPC shows a significant change in snow accumulation and ablation with natural forest disturbance and clearcut logging, although the magnitude of change varies with location, elevation, aspect and forest cover type. Post-MPB and post-wildfire snow surveys at ML indicate that disturbance has a delayed and intermediate effect on snow accumulation and melt relative to green mature forest and clearcuts. Once naturally disturbed stands have been salvage logged, or extensive areas of green forest in upland watersheds typical of interior BC have been clearcut, results at UPC show that earlier snowmelt and synchronization of melt runoff over an extensive area can advance the timing of spring high flows, significantly increase April water yield and decrease yield in June and July. Such shifts in the hydrograph could increase flood risk, affect aquatic habitat and negatively affect irrigation water supplies where storage is not available. Research at ML indicates that retention of some attacked and moderately burned stands, particularly those stands with understorey vegetation, could mitigate the immediate effects of salvage clearcut logging, reducing the increase in water available to generate spring runoff and possibly delaying the timing of runoff relative to clearcuts.

Ongoing work at the ML and UPC research sites will help improve our understanding of and ability to evaluate hydrologic response to forest disturbance. This will be enhanced with detailed analyses of snowmelt contributions to streamflow response at intermediate logging extents and the synthesis of forest–snow interaction survey from sites throughout the interior of BC. The results will guide decisions regarding the benefits of dead or damaged stand retention versus salvage logging and the assessment of cumulative effects on flood risk, aquatic habitat and water supplies. These long-term studies also provide the background from which to evaluate the potential additional effects of climate change and to evaluate the performance of models used to predict hydrologic change in snow-dominated watersheds.

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