

The Canopy Structure and Snow Hydrology of Managed Lodgepole Pine Stands Compared with Beetle-killed Stands

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Introduction

Mountain pine beetles (*Dendroctonus ponderosae*) have killed a large portion of canopy-forming pine trees across more than 14 million ha in the Interior of British Columbia (BC Ministry of Forests and Range 2008). This raises hydrologic concerns because research shows an intense beetle infestation can increase spring floods (e.g., Bethlahmy 1975, and as summarized by Uunilla et al. 2006). In order to capture economic value and re-establish healthy forests, the province's Chief Forester has also approved accelerated harvesting of beetle-killed stands (BC Ministry of Forests and Range 2004). A large part of the Interior is therefore undergoing severe forest disturbance by a combination of beetles and logging. A severe beetle infestation, however, initiates a very different sequence of changes in stand structure than that which usually occurs after clearcutting. The effects of these two disturbance types on snow hydrology are therefore expected to differ for a period of decades. A better quantitative understanding of these differences would allow hydrologists to make more reliable predictions about the stand- and watershed-level effects of salvaging versus retaining beetle-killed pine stands. Forest managers and hydrologists are particularly interested in knowing the potential

effects of different post-infestation watershed conditions on flood magnitudes (e.g., Forest Practices Board 2007; Snetsinger 2007).

Evergreen conifers affect snow hydrology by increasing interception loss and by decreasing the rates of melt and vaporization of snow stored on the ground (i.e., ablation). Clearcutting therefore tends to increase both snow storage at the end of the accumulation season and ablation rates during the main ablation season. In a review of the literature, Winkler (2001) found that in 32 comparisons of snow in conifer forests versus clearcuts, an average of 35% more snow accumulated in openings than in the forest. Clearcutting in the province's interior affects ablation even more with snow loss rates in clearcuts of 1.4, 2.0 (Boon 2007, 2009), and even 2.5 times (Winkler et al. 2005) greater than nearby mature forest. These differences decrease over time with hydrologic recovery and have been found to approach zero (i.e., 100% recovery) at an average tree height of 20 m on the west coast (Hudson 2000). In the interior, Winkler (2001) and Winkler et al. (2004) concluded that other parameters such as crown length, crown closure, main canopy height, and/or basal area were better for predicting recovery. Although this suggests that the hydrologic recovery of managed stands (i.e., plantations and naturally revegetated

clearcuts) is not a simple function of average tree height, it does imply that the recovery of managed stands is largely a function of measurable stand parameters that increase continuously during early stand development. Therefore, estimates of the hydrologic recovery of managed stands can be derived by combining predictions of structure from stand development models and predictions of recovery as a function of structure from similar references. In principle, a similar procedure could be followed for beetle-killed stands, but this may be problematic because the structure and development of killed stands are more complex than managed stands.

Beetle-killed stands are composed of dead overstorey trees and variable amounts

of residual live trees. The structure of killed stands in the future depends on the stand's initial state, deterioration rates of the dead trees, growth rates of residual live trees, and regeneration rates, all of which vary between stands (Coates et al. 2006). This introduces more spatial and temporal variability to the structure of killed stands than reforested clearcuts. Researchers have previously explained stand-level differences in clearcut equivalence using parameters such as average tree height that are more appropriate for healthy managed stands than for beetle-killed stands. We need to understand changes in the structure and snow hydrology of beetle-killed pine stands during the first decades after disturbance compared with managed stands using parameters

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This project aimed to improve our understanding of the hydrologic effects of salvaging versus retaining beetle-killed pine stands. More specifically, the objectives were to:

1. Describe stand-level snow accumulation and ablation rates in structurally diverse natural and managed pine stands relative to nearby recent clearcuts so that standardized clearcut equivalencies can be compared between widely separated stands.
2. Explain the differences in clearcut equivalencies as functions of fisheye photo-derived stand structure parameters that are applicable to all stands.
3. Characterize clearcut equivalencies and stand structure parameters as functions of time since logging in managed stands and time since attack in beetle-killed stands during the first three decades after disturbance.

Study Sites

The Baker, Moffat, Rosita, and Vanderhoof study sites (Figure 1) were established in an area spanning 250 km east–west and 180 km north–south on the Fraser Plateau of British Columbia approximately centred on the region affected by the latest mountain pine beetle infestation (Taylor and Erickson 2007). Elevations ranged from 880 to 1240 m, but in the study sites all plots were located within 4.6 km distance and 24 m elevation of each other. Three biogeoclimatic zones are represented—the Montane Spruce, the Sub-Boreal Pine–Spruce, and the Sub-Boreal Spruce. Although the differences in location, elevation, and BEC zone between study sites introduce variability, this is considered advantageous because it increases the representativeness of this study.

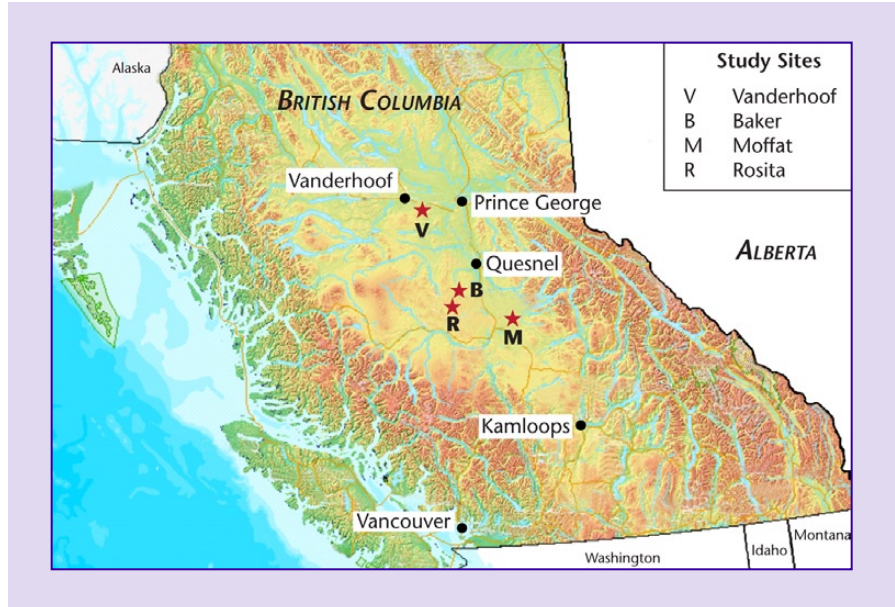


Figure 1. Study sites on British Columbia's Fraser Plateau.

Slopes in all plots were 7% or less. Each study site contained five to seven plots in pine-leading stands including a recent clearcut (trees < 1 m tall), one or two partially recovered managed stands, and two to four natural stands. The intent was for each study site to provide a sample of managed and natural stands with as much between-stand structural diversity as possible. Because of the beetle infestation, no old healthy stands were available as controls. Snow in a recent clearcut was used at each study site to standardize the accumulation and ablation parameters for treed plots as described below. For logistical reasons, some plots were located within 20 m of a substantially different forest type and plot BCC was located in a 2-ha clearcut surrounded by beetle-killed pine. In 2005, natural stands across all study sites ranged in age from 44 to 213 years; the managed stands had a maximum age of 33 years since logging according to the B.C. Ministry of Forests and Range Vegetation Resources Inventory (VRI; www.for.gov.bc.ca/hts/vri/intro/index.html). Table 1 (page 34) summarizes plot characteristics by study site.

Methods

Snow Surveys and Parameters

Plots were established by installing 36 snow survey points (rebar and bamboo poles) on 10-m centres in a square grid. Average snow water equivalent (SWE) for plots was calculated from 36 depth measurements and one density measurement in a snow pit next to the plot at the time of each survey. The parameter used to compare snow storage between plots was SWE at the beginning of the main ablation period (SWE_1). This was intended to represent the SWE at the start of the most rapid, sustained ablation period, generally lasting 2–4 weeks, and not the maximum SWE. In 2006 and 2007, the dates on which SWE_1 was measured (T_1) were based on 10-point reconnaissance snow surveys within 10 km of each study site at 1–2-week intervals. In 2008, measurement dates were based on snow surveys of all plots at 1–2-week intervals. In 2006 and 2007, the date and SWE at the end of the main ablation period (T_2 and SWE_2) were estimated from aerial photo flights of plots at approximately

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Table 1. Plots, stand characteristics, and snow data for the Baker (B), Moffat (M), Rosita (R), and Vanderhoof (V) study sites.

Plot	Age (years) ^a	Age ^b	Height (m) ^c	Stems per hectare ^d	Dead (%) ^e	Basal area, red to green (m ² /ha) ^f	Gap (%) ^g	Transmittance (%) ^h	Average SWE (mm) ⁱ	Average ablation rate (mm/day) ^j	Average SWE ratio ^k	Average ablation ratio ^l
BCC	2	2	0	0	NA	0	92	89%	214	6.0	1.00	1.00
BOD1	216	3	15	1312	69	14.2	61	30	138	3.7	0.65	0.61
BOD3	211	3	15	550	75	6.2	74	43	126	4.2	0.60	0.70
BON	126	126	14	4103	47	30.8	41	23	116	2.9	0.54	0.48
BRC1	8	8	4	1312	0	4.5	96	73	149	4.9	0.70	0.82
BRC2	33	33	10	1025	40	14.1	57	39	129	3.7	0.61	0.61
BYN	126	2	14	3853	77	13.4	61	31	149	4.5	0.72	0.74
MCC	2	2	0	0	NA	0.0	100	100	109	5.2	1.00	1.00
MO1	128	3	17	2237	79	8.9	61	39	142	4.1	1.30	0.81
MO3	128	3	21	1774	73	12.4	57	41	115	4.0	1.05	0.77
MRC1	10	10	0	0	NA	0.2	100	94	126	5.4	1.16	1.11
MRC2	29	29	10	1537	36	18.7	48	26	96	2.3	0.87	0.46
RCC	2	2	0.0	0	NA	0.0	100	93	106	6.0	1.00	1.00
ROD1	199	25	8.0	2099	13	18.7	69	43	95	3.5	0.92	0.60
ROD2	213	25	5.0	1687	4	11.2	77	56	96	3.6	0.96	0.65
RON	213	2	15.5	1425	70	17.2	65	41	79	3.9	0.76	0.65
RRC1	12	12	3.3	325	4	2.1	96	74	110	4.4	1.11	0.78
RYN2	44	44	6.2	8847	3	26.4	60	27	86	3.7	0.87	0.65
VCC	2	2	0.0	0	NA	0.0	100	100	178	6.7	1.00	1.00
VOD1	135	135	7.3	1387	47	5.0	56	37	141	3.9	0.79	0.60
VOD2	135	5	11.8	1687	84	5.0	67	31	156	4.6	0.91	0.70
VRC1	13	13	4.6	1500	2	5.8	81	56	145	4.7	0.83	0.70
VYN	75	75	10.0	7648	23	28.7	42	25	133	3.5	0.78	0.55

^a Stand age from the Vegetation Resource Inventory as of 2005.

^b Years since stand replacement by logging or beetle-kill if more than 50% dead.

^c Average height of stems that were green-to-red and had DBH greater than 4 cm.

^d Density of all stems, green to snag, greater than 4 cm DBH.

^e Number of standing dead stems greater than 4 cm DBH per total stems; NA = no stems greater than 4 cm DBH.

^f Basal area of green-to-red stems having DBH greater than 4 cm.

^g Plot average gap fraction within 30° zenith angle.

^h Plot average portion of radiation transmitted in early April under clear skies.

ⁱ 3-year average SWE at start of the main ablation period.

^j 3-year average ablation rate.

^k 3-year average ratio of SWE in plot to SWE in clearcut.

^l 3-year average ratio of ablation rate in plot to ablation rate in clearcut.

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weekly intervals. The use of this method assumed that average SWE approached zero when the percentage of snow-covered ground reached 50%, as seen on aerial photos. In 2008, the dates on which SWE approached zero was estimated from ground snow surveys at 1–2-week intervals. Average ablation rate in each plot ($\Delta\text{SWE}/T$) during the main ablation period was similar to the “active melt period” of Faria et al. (2000) and was calculated as:

$$\Delta\text{SWE}/T = (\text{SWE}_1 - \text{SWE}_2) / (T_2 - T_1)$$

Stand Structure Measurements

In 2007, trees were surveyed in four fixed-radius subplots within each snow plot. All stems taller than 1.3 m were categorized by species and crown condition (green, green-red, red, red-grey, grey, and snag). In addition to the stem counts per unit area, a subsample of green-to-red pine trees was measured for diameter at breast height (DBH), top height, height at base of functional crown, and crown diameter, as described in Teti (2008). Defoliated pine trees (i.e., grey to snag) were not measured. Beetle-killed plots were defined as those having more than 50% dead stems.

Net radiation is generally the main source of energy for snow ablation in openings, conifer stands, and defoliated stands (Adams et al. 1998; Hardy et al. 1998; Spittlehouse and Winkler 2004; Thyer et al. 2004) and net radiation to the snow surface is greatest in the daytime under clear skies (e.g., Boon 2009). One of the most significant hydrologic issues is the potential for different stand types to generate differential snowmelt when the snow is melting fastest. Therefore, for hydrologic purposes, the portion of incoming solar radiation transmitted through the canopy (transmittance) is an important stand parameter. In 2008, direct, diffuse, and total solar radiation transmittances were estimated from hemispherical photos taken 1.1 m above ground at each point in each

plot. Above-canopy radiation values ($K_{\downarrow 0}$) were determined using Gap Light Analyzer[®] software (Frazer et al. 1999) for cloud-free conditions in early April at 52°N. Below-canopy radiation ($K_{\downarrow s}$) at each point was estimated as the sum of above-canopy direct and diffuse radiation in each of 113 sky segments in the celestial hemisphere times percent canopy gap in each corresponding segment of each hemispherical photo, determined using Scion Image for Windows[®] (Scion Corporation; www.scioncorp.com/). All fisheye images were analyzed for a latitude of 52° which was within 2° of the actual latitude of all study sites. The analysis of images with Scion software was identical in principle to the method used by Gap Light Analyzer to calculate radiation transmittance, the accuracy of which was confirmed by Hardy et al. (2004). Plot average transmittance was calculated as the average of $K_{\downarrow s}/K_{\downarrow 0}$ for each plot.

Sky-view factors were also calculated from fisheye photos (sum of gap fractions in 10° zenith angle increments weighted by the cosine of the zenith angle; Steyn 1980), but plot averages were highly correlated with plot average radiation transmittances (slope = 0.96, $r^2 = 0.98$; Teti 2008). Therefore, sky-view factors are not listed in Table 1.

Results

Table 1 summarizes selected stand structure parameters, 3-year average SWE ratios, and 3-year average ablation ratios in all plots. Although most of the descriptors in Table 1 reflect large and unambiguous differences between plots, one difference not shown is worth noting. The parameters derived from fisheye photos were highly heteroscedastic. The within-plot variability was highest in managed stands where crowns were starting to merge and in old stands where clumps and gaps had developed. The variability was lowest in plots having very low or very high amounts of canopy because all of the canopy parameters are constrained between 0% and 100%. Due to these

differences between plots, the sample sizes that would have been required to estimate plot average radiation transmittances to a fixed confidence limit varied by a factor of more than 12 (Teti 2008).

Ratios of Snow Water Equivalents and Ablation Rates

Average SWE ratios ranged from 54% to 130% and average ablation ratios ranged from 46% to 111%, but most of this variability occurred at the Moffat study site. At the Baker study site, average SWE ratios in treed plots ranged from 54% to 82%. At the Vanderhoof study site, treed plots had relatively small ranges in both parameters (SWE ratios from 78% to 91% and ablation ratios from 55% to 70%). At Rosita, SWE ratios in the five treed plots averaged 76% to 111% and ablation ratios ranged from only 60% to 78%. The Moffat study site was unusual in that average SWEs of three of the treed plots were greater than that in the clearcut. Plot MO1, a mature pine stand that was attacked by beetles in 2005, lost most of its needles by April 2007, and had a 30% higher average SWE, but a 19% lower ablation rate compared to the Moffat clearcut site. Plot MRC1, a 10-year-old managed stand, was the only treed plot that had a higher average ablation rate than the nearby clearcut.

Ratios of Snow Water Equivalents and Stand Structure

Average SWE ratios were regressed against plot average values of crown volume per unit area, square root of basal area, and canopy gap fraction within 30° of the zenith. When all plots were analyzed together, no statistically significant relations were found; however, when study sites were analyzed separately, positive correlations were evident between SWE ratio and canopy gap at three study locations (Figure 2, page 36). Similar results were found in regressions between SWE ratios and the square root of basal area by study site (not shown). The r^2 values

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between SWE ratios and canopy gap at the Baker, Moffat, Rosita, and Vanderhoof study sites were 0.49, 0.04, 0.69, and 0.70, respectively; r^2 values between SWE ratios and square root of basal area were 0.75, 0.05, 0.49, and 0.63, respectively.

Ablation Ratios and Stand Structure

Average ablation ratios were regressed against crown volume per unit area, basal area, and solar radiation transmittance. Ablation ratios were highly correlated with both radiation transmittance ($r^2 = 0.80$) and the square root of basal area ($r^2 = 0.79$) when all study sites were analyzed together (Figure 3). Because the data was standardized using SWEs and ablation rates in clearcuts and the ratios for the clearcuts equal 1 by definition, the data points for the clearcuts could be regarded as biased. With the clearcut data removed, the r^2 values for average ablation ratios versus transmittance and the square root of basal area were 0.64 and 0.60, respectively. The squared correlation coefficient between radiation transmittance and the square root of basal area was 0.95, indicating that these two parameters contain similar information about stand structure even though defoliated trees were not included in the basal

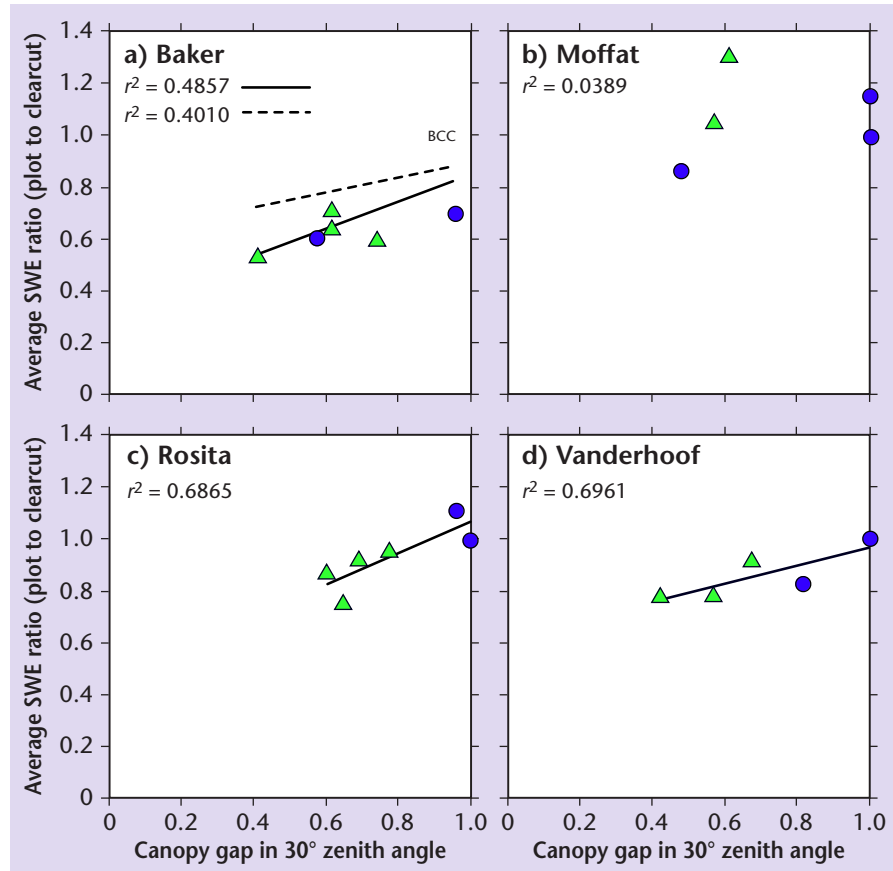


Figure 2. Average SWE ratios in natural (triangles) and managed (circles) stands versus canopy gap by study site. The dashed line in 2a is the regression obtained if SWE ratios are increased by 25% and BCC is excluded as discussed in the text.

area calculation. The slightly greater variance reduction in ablation rates by transmittance than by basal area could be because grey pine trees reduced solar radiation but were not included in the basal area calculation.

Effects of Logging Versus Retaining Dead Pine Stands Over Time

The most powerful way to estimate the effects of logging versus retention as functions of time is to measure the parameters of interest in managed stands and nearby killed stands that have similar disturbance dates over a long period. An alternative design, which substitutes space for time, samples killed stand/managed stand pairs (each with the same age) with multiple pairs that represent multiple years since disturbance. Another design, for which it is easier to find sites, involves:

- sampling killed stand/clearcut pairs having a range of ages since disturbance,
- sampling managed stand/clearcut pairs also having a range of ages since logging, and

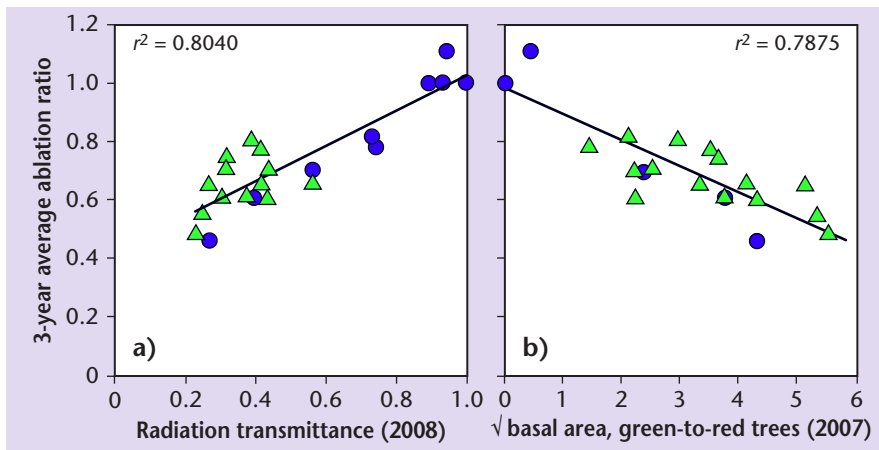


Figure 3. Average ablation ratios in natural (triangles) and managed (circles) stands versus plot average radiation transmittance and square root of basal area.

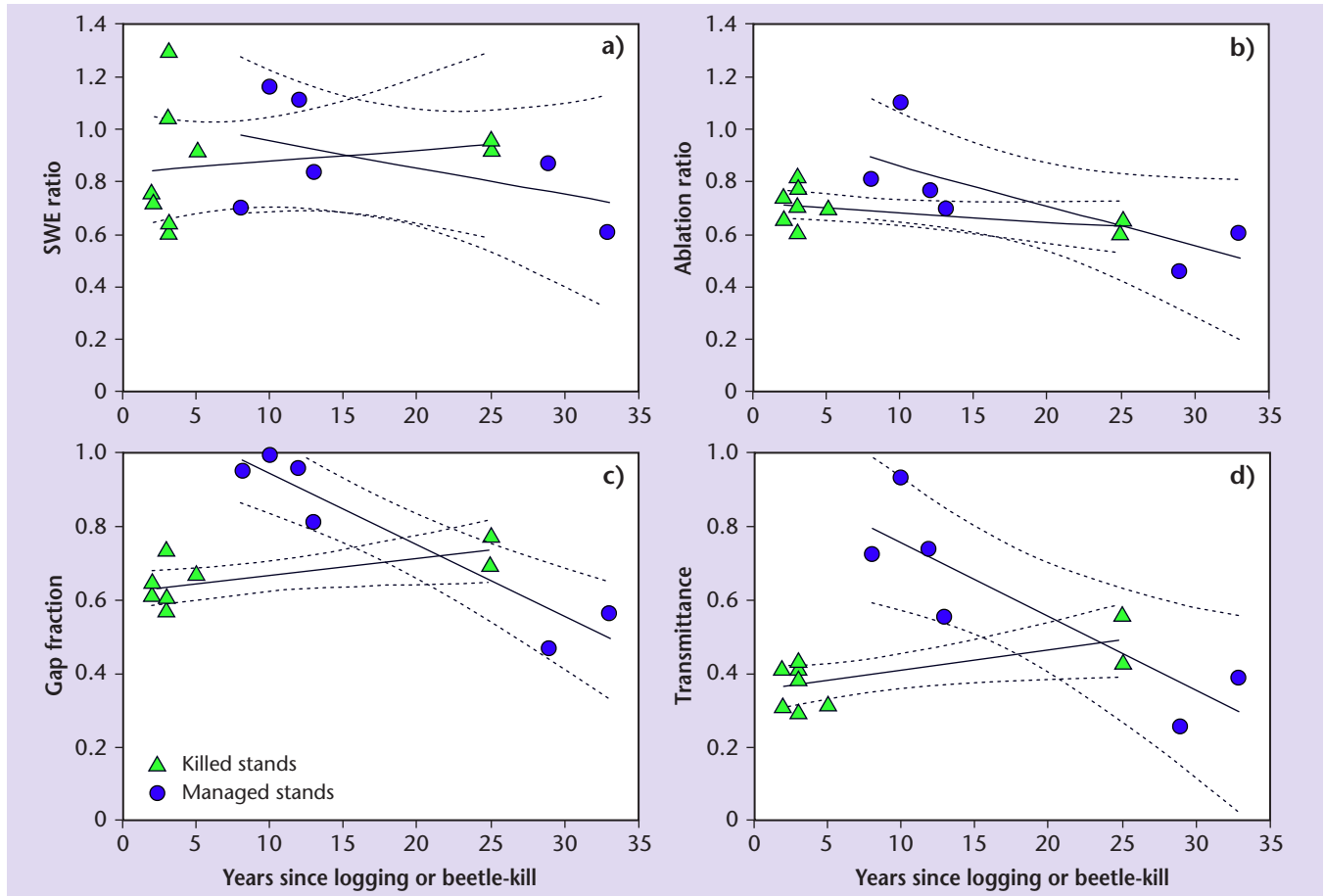


Figure 4. Average SWE ratios (a), ablation ratios (b), gap fractions (c), and solar radiation transmittances (d) versus time since disturbance in managed stands (circles) and killed stands (triangles). Regression lines and 95% confidence intervals are shown.

- modelling the parameters of interest as functions of time.

Comparisons are then made between regression lines rather than data pairs. With this model, the killed stands and managed stands need not be paired with each other and therefore do not need to have the same ages since disturbance. The stands also do not need to be near each other as long as each is near a recent clearcut. This study provides results using this model with six managed stand/clearcut pairs and nine killed stand/clearcut pairs.

The ages of beetle-killed stands (column 2, Table 1) are the estimated ages before beetle-kill (B.C. Vegetation Resources Inventory; www.for.gov.bc.ca/hts/vri/intro/index.html). For each of the nine beetle-killed plots,

the number of years since mortality was estimated from forest disturbance data fields in the VRI, from personal observation, and from beetle-spread maps (Taylor and Erickson 2007; <http://cfs.nrcan.gc.ca/subsite/mpb/historical-historique>). Figures 4a and 4b show SWE ratios and ablation ratios versus time for killed stands and managed stands. Since gap fraction affects SWE ratios and radiation transmittance affects ablation ratios, these parameters were also plotted versus time and regressions calculated (Figure 4c and 4d).

Edge Effects

Several plots exhibited changes in stand structure parameters with distance in from the plot edge. The plot with one of the largest such effects was BCC, which was located in

a 2-ha clearcut surrounded by beetle-killed pine. Due to the proximity of the beetle-killed trees to this plot, its southeast corner had a radiation transmittance of 44% compared with a plot average transmittance of 89%. This was the largest gradient in radiation transmittance observed in any plot. Openings of this size have been shown to experience more accumulation and slower ablation than larger openings (Golding and Swanson 1978). If that was the case in this plot, then the other (i.e., treed) plots at the Baker study site would have their SWE ratios biased low and their ablation ratios biased high because ratios were calculated with the corresponding clearcut values in the denominators. This would cause

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the regression line representing SWE ratio versus canopy gap for the Baker plots (Figure 2a) to fall below the data point representing plot BCC. In fact, this is what was observed. The value of the regression line at a canopy gap of 92% was 0.8 versus the observed value of 1 in plot BCC. The difference between the regression line in Figure 3a and the observed ablation ratio in plot BCC was smaller. At a radiation transmittance of 82% in plot BCC, the value of the regression line was 0.91 compared with the observed value of 1.

Discussion

Stand Structure Parameters

Studies show that stand structure can explain significant portions of the variability in snow accumulation and ablation rates when the data are standardized to clearcuts. For example, Winkler (2001) found that SWE ratios and ablation ratios were correlated with crown length, square root of crown volume, and crown closure. These parameters can be ambiguous and difficult to measure in killed stands because of the higher structural complexity. However, Winkler's (2001) results also show that crown length, crown volume, crown area, and basal area contain largely redundant information. Of the field-measured parameters, DBH (from which basal area is derived) is one of the more applicable in killed stands because it is easily measured and because the condition of crowns can be categorized. Optically measured parameters are also attractive because they are objectively quantifiable.

Canopy gap in a 30° zenith angle was chosen as a predictor of SWE ratios because previous results indicated that this was an effective and rational parameter in explaining plot average differences in snow storage (Teti 2003). Although leaf area index is an alternative, it is highly correlated with optically

measured canopy gap (or canopy density; e.g., Pomeroy et al. 2002) and is also generally estimated by optical methods. Radiation transmittance in early April under clear skies was chosen as a predictor of ablation ratios because of the importance of direct radiation as an energy source when snowmelt is fastest and because early April is the approximate mid-point of the main ablation period at these study sites. The selection of tree measurement parameters presented more of a challenge. When the tree surveys were planned, it was speculated that the crowns of defoliated trees would not affect SWE or ablation rates and therefore defoliated trees were counted but not measured. Thus, the effects of defoliated pine trees are not represented in the basal area measurements, although these effects are represented in the fisheye-photo measurements.

Snow Water Equivalent Ratios Versus Stand Structure

In contrast with other studies (Winkler 2001; Talbot and Plamondon 2002), no stand structure parameter was found that could consistently explain stand average SWE ratios across all study sites. When study sites were combined, neither canopy gap nor the square root of basal area was able to explain most of the variability in stand average SWE ratios. This could be due to a confounding effect of canopy if different winter weather between study sites causes the canopy to have different effects on net accumulation between sites and/or between years. The percentage of intercepted snow (Schmidt and Gluns 1991) and its fate (i.e., unloading, melt, or vaporization; Pomeroy et al. 1998) have been shown to vary with the weather. The fate of snow stored on the forest floor is also subject to variable ablation processes during the net accumulation season if weather conditions are conducive. For example, low canopy density tends to allow more snow to accumulate

during snowfall, but low canopy density could also result in more ablation of snow on the ground between snowfalls, depending on wind speed, air temperature, humidity, and solar radiation (e.g., Bernier 1990; Bernier and Swanson 1993). Differences in winter weather between study sites could therefore be sufficient to explain inconsistent correlations between late winter SWE and canopy structure parameters. The same argument applies to different correlations at one study site between years. The poor correlation between stand structure and net accumulation in the Moffat plots suggests that the Moffat site is a good location for further study of the complex wintertime accumulation and ablation processes.

Ablation Ratios Versus Stand Structure

Even with clearcut SWE ratios removed from Figure 3a, radiation transmittance in treed plots explained 64% of the variance in average ablation ratios across all study sites. The square root of basal area was similarly effective, suggesting that the processes by which canopy affects the year's main snow ablation event are simpler than those by which canopy affects net snow accumulation. As a result, both radiation transmittance and basal area appear to be good indices of relative snow ablation rates in pine-leading treed stands with a wide variety of disturbance histories and structures on British Columbia's Fraser Plateau. The fact that ablation ratios were better correlated with stand structure than were SWE ratios could indicate that the canopy on these sites interacts with snow in complex ways during the accumulation season, perhaps when temperatures are near freezing. During the net accumulation season, more gaps can allow more accumulation during snowstorms, but these gaps can also allow more ablation when the weather is conducive to vaporization and melt.

Stand Structure and Snow Hydrology Versus Time Since Disturbance

Snow water equivalent ratios were not well correlated with time since disturbance in either killed stands or managed stands and therefore the regression lines cannot be reliably distinguished (Figure 4a). Based on these data, salvaging killed pine stands did not seem to affect snow accumulation during the first three decades after disturbance. It is suggested that the canopy had an alternately positive or negative effect on snow mass balance during winter depending on weather, thus contributing to the poor correlations. Logging and retention differ somewhat more in their effects on ablation rates (Figure 4b). Killed stands and cutblocks less than 5 years old are well represented and clearcuts have ablation ratios of 1 by definition, even though the clearcut points at co-ordinates (0,1) in Figure 4b were excluded from the regression. If the linear regressions are taken as approximations of temporal changes in ablation ratios and if one is willing to accept an alpha error probability greater than 5%, then this study's results suggest that:

- During the first 5 years, logging increases ablation rates by an average of 43% more than a severe beetle infestation.
- 10 years after disturbance, managed stands have ablation rates 24% higher than retained stands.
- After 25 years, no difference exists in ablation rates between logged and killed stands.

Although snowmelt is the ablation component of interest for runoff generation, it was not measured. Therefore, it is useful to consider the possible correlation between melt rates (not measured) and ablation rates ($\Delta SWE/T$). Melt is related to ΔSWE as follows:

$$\text{Melt} = \Delta SWE - \text{net vaporization} + \text{new precipitation}$$

Based on the literature, average net vaporization of snow is expected to be approximately 1 mm/day in clearcuts and younger managed stands and about 0.25 mm/day in forested stands during the ablation season (Bernier 1990; Bernier and Swanson 1993). Rain and snowfall during the ablation season appeared to be much less than SWE at the start of the ablation season based on snow pit observations, but this cannot be confirmed due to the absence of nearby weather stations. However, it is supported by the relative consistency of calculated ablation rates in clearcuts across study sites. Three-year average ablation rates in the four clearcuts ranged from 5.2 to 6.7 mm/day (Table 1). Ablation rates were also similar within most clearcuts between years (data not shown) ranging from 5.6 to 6.7 mm/day in BCC, 4.1 to 5.9 mm/day in MCC, 4.0 to 7.0 mm/day in RCC, and 5.7 to 7.9 mm/day in VCC. Precipitation events during ablation seasons would be expected to cause variability in the calculations of average ablation rates within and between clearcuts so the absence of high variability implies that large precipitation events were uncommon. Precipitation and vaporization during the ablation season would tend to cancel out, but the net effect is unknown. Even though vaporization might be four times greater from clearcuts than from forested stands (Bernier 1990), anecdotal observations of fresh snowfall in snow pits suggest that precipitation during the ablation season is of the same order of magnitude as vaporization and that estimates of $\Delta SWE/T$ are reasonable approximations of melt rates.

Figure 4 shows that evolving beetle-killed stands are better differentiated from evolving managed stands by their structure than by their snow

hydrology. Killed stands have more canopy structure than managed stands until at least 15 years after disturbance and perhaps for 20–25 years. After 25 years, managed stands tend to have more structure (i.e., lower gap fraction and radiation transmittance) than beetle-killed stands. However, the relatively small number of plots and absence of plots in stands that were killed 5–25 years earlier means that the relationships in Figure 4 could be improved with new data from more sites. For example, the time required for dead stems to fall down and for new seedlings to regenerate in killed stands is likely more variable than is suggested in Figures 4c and 4d.

Several plots were located within 20 m of a significant polygon boundary, but only plot BCC is discussed here because it is considered to have experienced the largest edge effects. This plot received enhanced snow accumulation because of the small size of the opening in which it is located. The SWE ratio regression line for the Baker study site in Figure 2a suggests that plot BCC had an average of 1/0.8 or 25% more snow at the start of the main ablation season than would have been expected based on its canopy gap value. This indicates that snow storage in small openings is affected by vegetation outside the 30° zenith angle (e.g., Spittlehouse et al. 2004), and agrees with Veatch et al. (2009) who also noted that the shaded sides of forest openings had 25% more snow in late winter than most parts of large openings. This suggests that the SWE ratios in Baker study site plots should be 25% higher than those reported here. In this case, plot BCC would have a SWE ratio of 1.25 and the point for a “representative” clearcut would be at x,y location of (1,1) in Figure 2a. Also, plot BCC should not be included in the regression because

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it belongs to a different population. Late winter snow storage is reduced by wintertime ablation, which in turn is affected by wind speed and solar radiation during winter ablation periods. Both of these processes are affected by forest features beyond that which can be seen with a 30° zenith angle over a plot. Unlike SWE ratio, the ablation ratio in plot BCC is not an outlier in the SWE ratio versus radiation transmittance relationship in Figure 3a. This supports the validity of springtime radiation transmittance as a regulator of springtime snow ablation rates over a wide range of stand types.

Conclusions

Average snow ablation ratios changed consistently with solar radiation transmittance and basal area across a wide variety of lodgepole pine stands and a large geographic area. No similarly universal relations were found between average SWE ratios and stand structure, but SWE ratios were positively correlated with canopy gap in three of the four study sites after correcting for enhanced snow storage in the small clearcut at the Baker site.

Because SWE ratios were highly variable at all post-disturbance ages, the results do not indicate that salvage logging increases snow storage at the beginning of the main ablation season; however, if interpolation is tolerated, then the results indicate that salvage logging will increase snow ablation rates for up to 25 years. After 30 years, most managed stands should have slower ablation than killed pine stands which have developed naturally for that amount of time. The rates of deterioration and recovery of killed stands are likely more variable than that suggested by this small sample, but the results should nevertheless help watershed managers make decisions about the short- to

medium-term hydrologic effects of salvaging versus retaining beetle-killed pine stands.

The accuracy and representativeness of these results could be improved by increasing the number of killed stand/clearcut pairs and the number of managed stand/clearcut pairs at post-disturbance ages greater than 10 years. New results could be made compatible with those reported here by reporting SWE and ablation rates in stands as ratios to SWE and ablation rates in nearby clearcuts.

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