



Effects of overstory mortality on snow accumulation and ablation – Phase 2

Final Report

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MPBP Project # 7.33

July 16th, 2009
(distribution version)

Abstract

Pine dominated forests in B.C. are undergoing changes due to extensive beetle mortality and salvage harvesting operations. As a result, large areas of formerly mature pine-leading stands are being converted to a patchwork of cut blocks, plantations, and deteriorating beetle-killed stands. There is an increasing recognition among hydrologists that distributed hydrologic models are well-suited to predict the watershed-scale effects of these changes on streamflow, especially under different scenarios of salvage logging and climate change. This project assists in the development of these models by providing stand-level data on the structure and snow hydrology of plantations and beetle-killed stands at several different times after disturbance.

The ratios of snow ablation rates in treed plots to those in adjacent clearcuts (snow ablation ratio) were found to vary consistently with plot average solar radiation transmittance over a wide variety of Lodgepole pine stands and a large geographic area. No similarly universal relation was found for snow storage at the start of the main ablation season. It was hypothesized that this could have been due to different winter weather between study areas interacting with the forest canopy to cause sometimes negative and sometimes positive relations between the canopy and net snow accumulation.

These results provide a large data set representing a wide variety of stands over a large geographic area. This will help watershed modellers correlate forest cover data with stand-level parameters that are used in snow interception and ablation algorithms. The outcome is expected to be improved accuracy of predictions of hydrologic changes under different forest disturbance regimes.

Key words: mountain pine beetle, solar radiation transmittance, watershed hydrology, snow ablation, aerial photography, canopy photography

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1 Introduction

Pine dominated forests in B.C. are undergoing rapid change due to mountain pine beetles (MPB) and salvage logging with large expected consequences on stand- and landscape-scale hydrology. The beetle epidemic will result in patchworks of recovering plantations and killed stands across many watersheds. In the first phase of the project, a network of plots in natural (deteriorating) and managed (mostly recovering) pine stands were established, plot characteristics were documented, and one year of snow data were collected. In the second phase, snow monitoring was carried out for two additional seasons and plot characteristics were further sampled to document rates of change in stand structure due to the growth and deterioration of trees.

Watershed modeling is one of the few methods for predicting the combined effects of pine beetles and logging over large watersheds but this requires stand-level data on the snow hydrology of plantations and killed stands at different times after disturbance. This project is helping fill that information gap.

2 Project Objectives and Results

2.1 Overview

The objectives of this project were to:

1. characterize snow hydrology and stand structure in pine-leading stands having a wide variety of ages and disturbance histories on the Fraser Plateau,
2. establish a permanent network of research plots in growing and deteriorating pine stands for multidisciplinary use,
3. identify relationships between snow accumulation, snow ablation rate, stand type, and stand structure, and
4. test new methods for documenting stand structure.

This project was a continuation of MPBI 8.39 which ran from late 2005 through March 31, 2008 which was described in Teti (2008). This report describes the work that was done between April 2008 and March 2009 and summarizes cumulative project results from both project phases.

2.2 Project Objectives

In the aftermath of the current MPB infestation, most formerly mature pine stands have suffered a high percentage of overstory mortality. Therefore, in order to predict the marginal effect of salvaging versus retaining killed pine stands, we need to do so in comparison with attacked, but unlogged stands rather than in comparison with mature, healthy stands which has been common in the past. This project is the first attempt to compare snow hydrology changes over time in plantations versus killed stands.

The broad objectives were to document snow storage, snow ablation rates, and stand structure in a network of pine stands representing a wide variety of natural and managed stands over a large geographic area. Extension objectives were to make the results known to forest managers, licensees, and scientists through workshop presentations, publications, and websites.

More specific objectives included the sharing of raw data with project participants and the development of semi-quantitative guidelines to help managers minimize hydrologic risks and/or uncertainty while planning pine salvage operations.

2.3 Research Methods

2.3.1 Plot establishment

Five new study areas (Baker, Moffat, Rosita, Taseko, and Vanderhoof) were established during phase 1 of this project as described in Teti (2008). Data from the Mayson study area was included in phase 1 of this project but Mayson Lake was not included as part of phase 2. This report describes the work done up through phase 2 that was not included in the previous report, and summarizes combined results for phases 1 and 2.

2.3.2 Snow surveys

In 2006 and 2007, snow storage and ablation rates were determined by a single detailed ground snow survey followed by aerial surveys. In 2008, snow was repeatedly surveyed on the ground in order to better estimate SWE and ablation rates using methods previously described (Teti, 2008).

2.3.3 Tree surveys

Vegetation surveys were conducted in the summer of 2007 in all 24 treed plots in the five study areas. In each plot, trees were surveyed in four circular sub-plots of

50 or 200 m² each depending on the estimated stem density. All stems taller than 1.3 m were categorized by species and crown condition. Tree crowns were categorized as green, green-red, red, red-grey, grey, and snag. In addition to the stem counts, a sample of up to 20 trees between 2 and 4 cm DBH and up to 20 trees > 4 cm DBH were measured (the first 10 green trees and up to 10 red trees) in each circular plot. If a tree had a DBH greater than 2 cm its height and DBH were recorded. If DBH was > 4 cm, additional measurements included height to base of functional crown and crown diameter. Crown diameter was estimated along north-south and east-west lines by visually projecting crown perimeters down to the ground. Grey trees and snags were not measured. Stand ages as of 2005 were obtained from the British Columbia Ministry of Forests and Range Vegetation Resources Inventory with the exception of plot TON whose VRI age of 68 was changed to 130 after counting rings in cores from two representative canopy-forming trees. Killed stands were defined as those having more than 50% of stems dead at the time of the surveys.

2.3.4 Coarse Woody Debris surveys

In the summer of 2006, coarse woody debris was surveyed on 26 of the 29 plots using methods similar to those of Densmore, et al. (2004). Within each 50 by 50 metre plot, four transects of 35.4 metres were set up in the cardinal directions and centred on the plot as shown in Figure 1. Along each transect, data were collected on each piece of woody debris if it met these criteria; at least 5 cm diameter, at least 5 cm vertical relief above the forest floor, and its axis forming an angle of less than 45 degrees from the horizontal. For each piece, distance along transect, diameter, height above the forest floor, direction of fall, and decay class (Bartels et al., 1985 as cited by Stevens, 1997) were recorded. Stumps and stems were tabulated separately. Volume and pieces per unit area were summarized by ecoclassification, stand age, and height above ground.

2.3.5 Canopy photography and light parameters

Hemispherical canopy photos were taken at each of 36 points in all treed plots in 2006 and were repeated in 2008 in order to document changes due to growth of live trees and deterioration of dead trees. In clearcuts, photos were taken only at a subset of points and only in 2006. Photos were analyzed for canopy density and canopy gap (gap = 1-density) in two different coordinate spaces, one based on polar coordinates and the other based on sun position as a function of time of day and time of year. The former was for the calculation of diffuse radiation transmittance, sky view factor, and canopy gap within different zenith angles. The latter was for calculation of direct radiation transmittance. Field and analytical methods are described in detail in Teti (2008). The same parameters were



calculated independently from photos taken in 2006 and 2008, thus allowing changes in plot averages to be determined.

2.3.6 Repeated vertical aerial photography

Vertical aerial photos of all plots were taken from fixed-wing aircraft on different dates between March 2006 and March 2009. The original purpose of the aerial photography was to estimate the dates of snow disappearance in the first phase of the study (2006 and 2007). However, it was also discovered that aerial photos taken when there is complete snow cover on the ground and an overcast sky provide a unique view of trees, allowing interpretations of forest structure that are not possible on conventional aerial photos. These photos were used to document defoliation, blowdown, and crown diameter growth over time, and to estimate canopy gap for comparison with results from ground-based hemispherical photography.

2.3.7 Oblique aerial photography

Helicopter-based oblique aerial photos were taken of some plots in 2008 and 2009 in order to test the feasibility, accuracy, and possible cost-effectiveness of estimating the percentage of solar radiation transmitted at the plot-scale by remote sensing.

2.3.8 Stand parameters and parameter relationships

Table 1 is a conceptual model of site and stand characteristics with the most independent variables in the first column and the snow hydrology parameters in the last column. Although climate, weather, and soils are some of the most independent variables, only time since disturbance and disturbance type (logging or beetle-kill) are represented in this project. The stand structure parameters in columns 2 and 3 depend on those in column 1 but they control those in column 4, which are the snow parameters of interest. Parameters in solid boxes were quantified in some way for this project and those in bold text were used to develop empirical relationships. It is useful to explore relations among parameters in the first three columns because this reinforces the connectedness between the fields of forest ecology, forest mensuration, and forest hydrology. Ultimately, the most important, relationships for this project are those that improve our ability to predict snow accumulation and ablation rates as functions of variables in columns 1 to 3. More specific definitions and rationales for parameter selection follow.

2.3.9 Snow parameters

The parameter used to compare snow storage between plots was snow water equivalent (SWE) at the beginning of the sustained ablation period (the “active melt period” of Faria et al., 2000) because this is the amount available for rapid spring melt. If maximum SWE occurs before the start of the main ablation period the difference could be due to vaporization, which in young juvenile stands and clearcuts, is likely in the range of 1 mm/day on many winter days (Bernier, 1990; Bernier and Swanson, 1993). Therefore, SWE at the start of the main ablation period has a larger effect on spring runoff generation than does absolute maximum SWE that might have occurred weeks earlier. In the years 2006 and 2007, a single snow survey was done in each plot just before the main ablation period and the dates of snow disappearance were estimated from aerial surveys, thus providing a two-point SWE time series for each plot. The dates on which to do ground surveys were based on weekly reconnaissance snow surveys near each study area. The second point on the SWE curves in 2006 and 2007 were estimated by sequential aerial photography at approximately weekly intervals based on the assumption that plot average SWE was rapidly approaching zero when half of the ground was snow-free. In 2008, SWE time series were estimated from six ground snow surveys of all plots.

2.3.10 Tree survey parameters

Raw data from tree surveys were used to estimate percent species composition, percentage of trees in the green, red, grey, and snag categories, basal area of green and red stems, volume of green and red crowns per unit area, and the crown footprint of green and red crowns. Basal area and other metrics of grey stems were not calculated because grey trees were not measured.

2.4 Results

2.4.1 Snow storage and ablation rates

In most years and most plots, the main ablation period started in mid- to late-March and ended in mid-to late-April. SWE's varied considerably between plots, between study areas, and between years, ranging from 43 mm in a mature grey-attacked stand in 2006 in the Rosita study area to 311 mm in the clearcut at the Baker study area in 2007. Average ablation rates ranged from 1.2 mm/day in the 30 year-old plantation at the Moffat study area in 2008 to 7.0 mm/day in the clearcut at the Rosita study area in 2008. Table 2 summarizes selected stand structure parameters, SWE's, and ablation rates in 2006 through 2008. Since the

purpose of this project is to investigate the effects of stand characteristics on SWE and ablation rate rather than the effects of differences between study areas or years, SWE and ablation rate in each plot were divided by SWE and ablation rate in the nearby clearcut to get a “SWE ratio” and an “ablation ratio” for each year. These were averaged over the three years to get an average SWE ratio and an average ablation ratio for each treed plot. SWE ratios and ablation ratios in clearcuts are equal to 1 by definition.

Average SWE ratios in the 24 treed plots ranged from 54% to 130% and average ablation ratios ranged from 46% to 111%. In the Baker study area, average SWE ratios in treed plots had a smaller range of 54% to 82%, indicating that all treed plots had lower SWE than the clearcut. In the Vanderhoof study area, treed plots had small ranges in both SWE ratios (78 to 91%) and ablation ratios (55 to 70%). At Rosita, SWE ratios in treed plots averaged 76 to 111%, with only the 12 year-old plantation having a higher average SWE ratio than the clearcut. Ablation ratios in the treed plots at Rosita ranged from only 60 to 78%. The Moffat study area was unusual in that SWE's in three of the treed plots were, on average, greater than SWE in the clearcut. Plot MO1, a mature pine stand that was attacked by beetles in 2005 and which lost most of its needles before April 2007 (Figure 16 in Teti, 2008), had an average of 30% higher SWE but 19% lower ablation rate than the Moffat clearcut. Plot MRC1, a 10 year-old plantation, was the only treed plot in the project that had a higher average ablation rate than the nearby clearcut.

2.4.2 Canopy characteristics from hemispherical canopy photos

The phase 1 report described the methods by which optical canopy characteristics and solar radiation transmittance were estimated and summarized results from the 2006 photography. Very high correlations were found between the plot averages of diffuse transmittance and total transmittance, and between the plot averages of sky view factor and total transmittance. Both r-squared values were equal to 0.98, indicating that diffuse transmittance, total transmittance, and sky view factor contained very similar information about pine stands represented in this project.

The phase 1 report also documented differences in the variability of radiation transmittance within plots as well as between plots. Transmittance was highly heteroscedastic between plots, one of the implications of which was that the number of unbiased points required to estimate plot average solar radiation transmittance to within an accuracy of 5 percent transmittance ranged from less than 6 to more than 70 between plots. However, in this project the number of points sampled in the five main study areas was constant at 36. Therefore, the

confidence limits on plot average radiation transmittance differed between plots. The calculated 95 percent confidence limits ranged from < 1 percent transmittance to 8 percent transmittance.

The highest within-plot variability was found in plantations where crowns were starting to merge and in old stands having a wide variety of tree ages due to complex disturbance histories (Teti, 2008). Variability was low in plots with the lowest and highest average transmittances as shown in Figure 2. This is because the population bounds are 0 to 100, meaning that in order for the sample mean to approach zero or 100%, the sample variance must approach zero.

2.4.3 Snow storage versus 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 in a 30 degree zenith angle. When all plots were analyzed together, there were no statistically significant relations between SWE ratio and stand structure. However, there were positive correlations between SWE ratio and canopy gap in three study areas when study areas were analyzed separately as shown in Figure 3. Similar results were found in regressions between SWE ratios and the square root of basal area. The r^2 values between SWE ratios and canopy gap at the Baker, Moffat, Rosita, and Vanderhoof study areas were 0.49, 0.04, 0.69, 0.70, while those between SWE ratios and square root of basal area were 0.75, 0.05, 0.49, and 0.63.

2.4.4 Snow ablation versus stand structure

Average ablation ratios were regressed against crown volume per unit area, basal area, and solar radiation transmittance. There were good correlations between ablation ratios and stand structure parameters when all study areas were grouped together. Ablation ratios in all plots were highly-correlated with both radiation transmittance ($r^2 = 0.8040$) and the square root of basal area ($r^2 = 0.7875$) as shown in Figure 4. Since the data were standardized using SWE's and ablation rates in clearcuts, 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 0.6362 and 0.6038 respectively. This suggests that plot average radiation transmittance and the square root of basal area contain similar information about stand structure, even though only the basal area of green to red trees was used in the basal area calculation.

2.4.5 Changes in stand structure over time

It has been shown that in this sample of plots, stand structure parameters derived from hemispherical photos (e.g. diffuse radiation transmittance, total radiation transmittance, sky view factor, and angular canopy gap) are highly correlated with one another, that radiation transmittance decreases with plantation age, and that it could take about 75 years for sites disturbed by wildfire to reach the level of radiation recovery achieved by plantations in 30 years (Teti, 2008). These conclusions regarding changes over time are based on a classic substitution of space for time (Morrison, 2008) which is necessary for short-term studies. However, due to relatively rapid changes that are occurring in these stands, this study also documents changes in the structure of individual plots over several years by ground-based canopy photography and aerial photography.

Hemispherical canopy photos were taken in all plots in 2006 and were repeated in all treed plots of the five main study areas in 2008. Figure 5 is a scattergram of plot average transmittances in 2008 versus those in 2006. Points above the $y=x$ line indicate increases in transmittance while those below the line indicate decreases. Increases suggest net deterioration while decreases suggest net growth but differences could also reflect measurement errors.

The plot with the most obvious net deterioration during the monitoring period was MO1. Aerial photos taken in April 2006 and April 2007 (Fig. 16 in Teti, 2008) reveal a dramatic change in tree crowns from yellowish-green to grey, indicating that trees in the plot had been attacked in the summer of 2005 and were mostly defoliated in the winter of 2006/07. None of the other mature pine stands showed as much visible change in structure during the monitoring period as plot MO1. A stem map based on the aerial photos indicated that 67% of the canopy-forming trees had turned from green to grey in that one-year period, an unusually rapid rate of needle drop. This agrees well with the 2007 vegetation survey in which an estimated 79% of stems > 4 cm DBH were dead. Calculated radiation transmittances in MO1 increased from 31% in 2006 to 39% in 2008. This 8 percent increase in radiation transmittance could be might be less than expected in a stand where more than two-thirds of canopy forming trees were defoliated. However, inspection of hemispherical photos taken at the same ground locations in those two years confirmed that the binarized versions of the photos represented the actual crown conditions in the two years reasonably well and that the calculated canopy data should be accepted. Figure 6 is an example of pair of canopy photos taken at the same point in plot MO1 in those two years.

As a group, the plantations provide good examples of change over time. The plantations under 20 years old (since logging) were growing rapidly while the two

oldest ones (29 and 33 years since logging as of 2005) were attacked by beetles during the project. Differences in the health of young versus old plantations are evident in the 2007 tree surveys and on aerial photos taken between 2006 and 2009. The plantations BRC2 and MRC2 had mortalities of 40 and 36 percent respectively (in stems > 4 cm DBH) at the time of the 2007 vegetation surveys. Their radiation transmittances were estimated to have changed by +7 and +5 percentage points respectively between 2006 and 2008 as indicated by their plotting positions above the $y=x$ line in Figure 5. In contrast, the five younger plantations had no beetle-attack, exhibited vigorous growth, and had decreases in radiation transmittance with changes ranging from -3 to -17 transmittance percentage points. Figure 7 is a pair of binarized hemispherical photos taken at a typical point in plot BRC1 in 2006 and 2008. The growth of individual tree crowns and branches is clearly visible as expansion of silhouettes from the outside to the inside of the hemispherical photos.

Transmittances in plantations in 2006 and 2008 are shown in Figure 8 which are plotted versus age (years since logging). Plots that were re-photographed in 2008 have two points on the graph thus defining changes in two years as indicated by arrows. This Figure also shows the general relationship for transmittances versus age in 2006 before BRC2 and MRC2 were attacked. One would hypothesize that radiation transmittance in individual plantations would decrease over time with a slope similar to the overall relationship (an average of 2 percentage points per year). The change vectors for plantations with green trees have negative slopes, indicating decreasing transmittance at similar rates as the overall trend but the attacked plantations had change vectors with positive slopes, reflecting net deterioration more like the beetle-attacked mature plot MO1 than the non-beetle-attacked plantations.

Figure 8 and the linear regression of 2006 data in Figure 8 include the data points for clearcuts. Due to trees on the south side of plots RCC and BCC, those two plots had lower transmittances than would be typical of most of the area in clearcuts. Therefore, the regression in Figure 8 is also likely biased. A more accurate relationship of transmittance versus time in plantations would show the effects of a regeneration delay during which transmittance measured at a height of about 1 metre remains at 100 percent for 5 to 10 years, after which it decreases rapidly. This would be more accurately represented by removing the clearcut points from the regression relationship.

In phase 2, differences in stand structure and snow hydrology between plantations and killed stands were examined as functions of time since disturbance in order to enable a comparison between killed pine stands that are retained on the landscape and those that are salvage logged, as discussed below.

2.4.6 Marginal effects of salvaging versus retaining grey pine stands

Plantations and killed stands change over time as dead trees deteriorate and live trees grow. It is hypothesized that the changes over time and the differences between plantations and killed stands are reflected in measurable stand structure parameters, snow accumulation, and snow ablation rates. The marginal effects of salvage logging on snow hydrology at time t can be expressed as the ratio between snow storage or ablation rate in a plantation and that in a killed stand after t years, e.g.

$$\text{SWE}_{\text{plantation,tc}} / \text{SWE}_{\text{killed stand,tk}}$$

and

$$\text{Ablation rate}_{\text{plantation,tc}} / \text{Ablation rate}_{\text{killed stand,tk}}$$

where tc = time since clearcutting and tk = time since the stand was killed.

The most powerful way to detect these differences would be to measure SWE's and ablation rates in adjacent plantations and killed stands with replication over a number of years. However, the alternative method used in this project, substituting space for time, was to estimate SWE ratios and ablation ratios as functions of time for a sample of (killed stand) / (clearcut) pairs and the same parameters in a sample of (plantation) / (clearcut) pairs. Comparisons can then be made between regression lines rather than individual data points. By calculating standardized SWE ratios and ablation ratios data can be combined from plots in different locations. The killed stands and plantations do not have to be near each other as long as each one is near a clearcut. This study provides such a set of data with 6 plantation / clearcut pairs and 9 killed stand / plantation pairs.

The ages of beetle-killed stands in column 2 of Table 2 from the B.C.'s VRI are the estimated stand ages before the infestation. For each of the 9 plots which had been beetle-killed, the number of years since mortality was estimated from forest disturbance data fields in the VRI, from personal observation, and from beetle spread maps (<http://cfs.nrcan.gc.ca/subsite/mpb/historical-historique>). Figures 6a and 6b show SWE ratios and ablation ratios versus time for killed stands and plantations. Linear regression models and 95% confidence limits on regressions are shown. Because SWE ratios were correlated with gap fraction in three of the four study areas, and ablation ratios were correlated with solar radiation transmittance in all study areas, those stand parameters were also

plotted versus time and regression lines calculated. Regressions and 95% confidence limits are shown in Figures 6c and 6d.

2.5 Discussion

2.5.1 Stand Structure Parameters Related to SWE and Ablation Rate

Previous studies have shown that stand structure parameters can explain significant portions of the variability in snow accumulation and ablation rates when the data are standardized to clearcuts. Winkler (2001) found that SWE ratios and ablation ratios were correlated with crown length, square root of crown volume, and crown closure. Her ablation ratios were also correlated with the square root of basal area. However, that was prior to the current beetle epidemic. Given the complexity of pine stands containing large numbers of deteriorating trees, many of those stand descriptors are now problematic because the perimeters and internal characteristics of dead tree crowns are difficult to define. However, Winkler's (2001) results also show that crown length, crown volume, crown area, and basal area contain largely redundant information. Of the field parameters, DBH (and basal area) is one of the most attractive for use in attacked stands as long as crown condition is also noted. Optically measured parameters are also attractive in the aftermath of the beetle epidemic because they do not require any judgments about crown condition.

Canopy gap in a 30-degree zenith angle was chosen as a predictor of SWE ratios because previous results (Teti, 2003) indicated that it was an effective and rational parameter for explaining plot average differences in snow storage. An alternative is Leaf Area Index but LAI is highly-correlated with optically measured canopy gap (or canopy density, e.g. Pomeroy et al., 2002) and is generally estimated by optical methods anyway. Radiation transmittance in early April under clear skies was chosen as a predictor of ablation ratios because 1) net radiation is the major source of snowmelt energy in openings, conifer stands, and defoliated stands (Spittlehouse and Winkler, 2004; Thyer et al, 2004; Hardy et al., 1998); 2) the highest incoming radiation occurs on clear days; and 3) early April is the approximate mid-point of the main ablation period in these study areas. The selection of tree measurement parameters for this study presented more of a challenge. When the tree surveys were being planned, it was speculated that the crowns of defoliated trees would not affect SWE or ablation rates so defoliated trees were counted but not measured. Thus in this study, the effects of defoliated pine trees are represented in the canopy gap and radiation measurements but not in the basal area measurements.

2.5.2 SWE 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 ratio in this study. Neither canopy gap nor the square root of basal could explain most of the variability in stand average SWE ratios when study areas were combined. It is suggested that this could be due to a confounding effect of canopy when different winter weather between study areas causes different periodic ablation conditions during the net accumulation season. It has been shown that the percentage of intercepted snow (Schmid and Gluns, 1991) and its fate of (i.e. unloading, melt, or vaporization, Pomeroy, et al., 1998) vary with the weather. The fate of snow stored on the forest floor is equally 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 can also result in more ground-level ablation 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 areas could therefore be sufficient to explain inconsistent correlations between late winter SWE and canopy structure parameters. The same argument would apply to different correlations in one study area between years. The poor correlation between stand structure and net accumulation in the Moffat plots suggests that that study area might be a good location to study complex wintertime accumulation and ablation processes.

2.5.3 Ablation Ratios Versus Stand Structure

Even with clearcut SWE ratios removed from Figure 3a, radiation transmittance in treed plots explained 64 percent of the variance in average ablation ratios across all study areas. The square root of basal area was similarly effective, suggesting that the processes by which canopy affects the main snow ablation event of the year are simpler than those by which it 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 having a wide variety of disturbance histories and structures on the B.C. Interior Plateau. The better correlation between ablation ratios and stand structure than SWE ratios and stand structure could be that the former reflects a more consistent role of the canopy in reducing solar radiation whereas the latter reflects an alternating positive and negative effect of the canopy on net accumulation in winter. During the net accumulation season, more gaps can allow more accumulation during snowstorms but they can also allow more ablation when the weather is conducive to vaporization and melt.

2.5.4 Stand Structure and Snow Parameters Versus Time Since Disturbance

Figures 4c and 4d suggest that in these study areas, gap fraction and radiation transmittance in plantations and killed stands follow similar patterns of change versus time since disturbance. The regressions suggest that the values of those parameters in plantations cross the values in killed stands at 20 to 25 years. No such statements can be made about SWE ratios in plantations versus those in killed stands due to the high variability of SWE ratios (Figure 4a). This could be because stand structure affects net SWE through a combination of positive and negative effects depending on winter weather as discussed above.

The ability to discriminate ablation ratios versus time in plantations from those in killed stands is a little better as shown in Figure 4b. If one is willing to accept an alpha error probability greater than 5 percent, the regression lines (and the fact that ablation ratios in clearcuts equal 1 by definition) indicate that plantations have higher SWE ratios than killed stands for approximately 15 years and that they have lower SWE ratios than killed stands after 25 years. However, the small sample size and absence of plots in killed stands between the age of 5 and 25 years since attack means that the linear regression for killed stands in Figure 4b is very preliminary. The time required for dead stems to fall down and for killed stands to be regenerated is expected to be variable. It should be noted that Figures 4a, b, c, and d show data for plantations and killed stands with the same date of disturbance. If salvage logging is done x years after a stand is killed, then the data for plantations would be shifted x years to the left in Figure 4.

This comparison of changes in the structure and snow hydrology of plantations versus retained grey stands should be regarded as a first approximation. Retained grey stands are problematic because the full range of possible changes is not represented in this sample. For example, a killed stand with a large amount of secondary structure and in which the dead trees remain standing for 20 years would likely be represented by points below the killed stand regression lines in Figure 6. On the other hand, killed stands with a longer regeneration delay and in which the dead stems blow down after few years would be represented by points above the killed stand regression lines. However, considering climatic and biological uncertainty in the future, the full range of changes in plantations over time is also not represented in Figure 6. What Figure 6 and the methods described above do provide is a method for adding more information to these relationships in the future.

2.6 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 SWE at the beginning of the main ablation season and stand structure parameters. It is hypothesized that was due to interactions between canopy structure and different wintertime ablation conditions between study areas. This implies opportunities for more research on wintertime processes that affect net accumulation, especially in the Moffat study area.

There were systematic changes in the structure and snow hydrology of pine plantations after logging, and in killed stands after canopy mortality. The changes were as would be expected in healthy plantations due to growth and in attacked plantations due to deterioration. In the future, clearcuts and plantations are expected to produce faster snowmelt than severely-attacked pine stands for a period of 15 years after logging. However, after 25 or 30 years, plantations should have slower snowmelt than killed pine stands that have developed naturally for that amount of time, assuming that the plantations do not have serious health problems. Although the rate of deterioration and recovery of killed stands is subject to more variability than is suggested by this small sample, the results should help watershed managers make forest planning decisions over time periods of three decades or more.

The results point to a course by which future work could reduce uncertainty. One of the higher priorities is to measure SWE and ablation rates in killed stands approximately 10 to 20 years after disturbance and in nearby clearcuts. This would provide an improved sample of SWE and ablation ratios in killed stands and the results would be directly compatible with those reported herein.

3 Dissemination of Results

3.1 Papers Published

Teti, P. and R. Winkler. 2008. Snow hydrology and solar radiation in growing and deteriorating pine stands. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. *BC Journal of Ecosystems and Management* 9(3):136–138.

Redding, T., R. Winkler, P. Teti, D. Spittlehouse, S. Boon, J. Rex, S. Dubé, R.D. Moore, A. Wei, M. Carver, M. Schnorbus, L. Reese-Hansen, and S. Chatwin. 2008. Mountain pine beetle and watershed hydrology. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. *BC Journal of Ecosystems and Management* 9(3):33–50.



Teti, Patrick. 2008. Effects of overstory mortality on snow accumulation and ablation. Natural Resources Canada Mountain Pine Beetle Working Paper 2008-13. 34p.

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4 Acknowledgements

This project was funded by the Government of Canada through the Mountain Pine Beetle Program, a three-year, \$100 million Program administered by Natural Resources Canada, Canadian Forest Service. Publication does not necessarily signify that the contents of this report reflect the views or policies of Natural Resources Canada – Canadian Forest Service.

The following forest licensees contributed by helping with site selection, site protection, and road access: West Fraser Mills Ltd., Tolko Industries, B.C. Timber Sales, Canfor Corporation

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6 Appendices

Table 1. Conceptual model of site and stand characteristics and their relationships.

Increasingly dependent variables →			
Most independent variables	Stand characteristics	Mass and energy transfer regulators	Snow hydrology parameters
Time since disturbance	Tree height, crown diameter, and depth	Solar radiation transmittance	Snow storage
Disturbance type	Basal area	Canopy gap fraction	Snow ablation rate
(Climate)	Stems per hectare	Sky view factor	
(Weather)	Coarse woody debris volume and spatial distribution	Aerodynamic roughness	
(Soils)	Surface area of leaves and stems (LAI)		



Table 2. Summary of plot level data

Study Area	Plot Name	Age (1)	Age (2)	Height (3)	SPH (4)	Dead (5)	BA, R-G (6)	Gap (7)	SVF 06 (8)	T 06 (9)	T 08 (10)	2006		2007		2008		Avg SWE Ratio (13)	Avg Abl Ratio (14)
												SWE (11)	Abl Rate (12)	SWE (11)	Abl Rate (12)	SWE (11)	Abl Rate (12)		
Baker	BCC	2	2	0	0	NA	0.0	92%	82%	82%		152	5.6	311	5.7	179	6.7	1.00	1.00
	BOD1	216	3	15	1312	69%	14.2	61%	32%	31%	30%	97	2.9	194	3.5	122	4.6	0.65	0.61
	BOD3	211	3	15	550	75%	6.2	74%	45%	42%	43%	108	4.0	172	4.0	99	4.6	0.60	0.70
	BON	126	126	14	4103	47%	30.8	41%	18%	15%	23%	79	2.1	169	3.1	99	3.5	0.54	0.48
	BRC1	8	8	4	1312	0%	4.5	96%	85%	90%	73%	123	4.6	214	5.0	110	5.1	0.70	0.82
	BRC2	33	33	10	1025	40%	14.1	57%	32%	32%	39%	103	3.0	174	3.2	108	4.8	0.61	0.61
	BYN	126	2	14	3853	77%	13.4	61%	31%	31%	31%	126	4.7	191	3.5	131	5.2	0.72	0.74
Moffat	MCC	2	2	0	0	NA	0.0	100%	98%	100%		90	4.1	101	5.6	136	5.9	1.00	1.00
	MO1	128	3	17	2237	79%	8.9	61%	33%	31%	39%	83	3.8	182	6.5	160	2.0	1.30	0.81
	MO3	128	3	21	1774	73%	12.4	57%	29%	28%	41%	79	3.6	127	3.6	139	4.7	1.05	0.77
	MRC1	10	10	0	0	NA	0.2	100%	96%	99%	94%	107	7.1	118	5.4	154	3.6	1.16	1.11
	MRC2	29	29	10	1537	36%	18.7	48%	26%	23%	26%	53	2.4	116	3.3	118	1.2	0.87	0.46
Rosita	RCC	2	2	0.0	0	NA	0.0	100%	95%	93%		55	6.9	147	4.0	117	7.0	1.00	1.00
	ROD1	199	25	8.0	2099	13%	18.7	69%	45%	45%	43%	57	3.8	125	2.8	104	3.8	0.92	0.60
	ROD2	213	25	5.0	1687	4%	11.2	77%	57%	57%	56%	66	4.4	134	3.6	90	2.9	0.96	0.65
	RON	213	2	15.5	1425	70%	17.2	65%	41%	38%	41%	43	5.4	98	2.6	96	3.7	0.76	0.65
	RRC1	12	12	3.3	325	4%	2.1	96%	86%	90%	74%	81	5.4	150	4.0	100	3.7	1.11	0.78
	RYN2	44	44	6.2	8847	3%	26.4	60%	36%	41%	27%	62	4.1	112	3.0	85	4.1	0.87	0.65
Taseko	TCC	2	2	0.0	0	NA	0.0	100%	98%	99%		M	M	M	M	M	M	M	M
	TOD2	138	3-25	12.2	500	61%	10.1	64%	32%	40%	41%	M	M	M	M	M	M	M	M
	TOD3	158	3	12.4	337	73%	8.5	63%	38%	55%	42%	M	M	M	M	M	M	M	M
	TON	130	130	7.4	1525	36%	16.0	63%	35%	32%	40%	M	M	M	M	M	M	M	M
	TRC1	16	16	3.1	225	0%	0.5	96%	91%	94%	88%	M	M	M	M	M	M	M	M
	TYN	68.0	68	7.3	7648	0.4	31.9	58%	30%	21%	25%	M	M	M	M	M	M	M	M
Vanderhoof	VCC	2	2	0.0	0	NA	0.0	100%	99%	100%		103	7.9	272	6.6	158	5.7	1.00	1.00
	VOD1	135	135	7.3	1387	47%	5.0	56%	33%	28%	37%	67	2.3	209	4.5	149	4.7	0.79	0.60
	VOD2	135	5	11.8	1687	84%	5.0	67%	39%	40%	31%	104	3.6	214	5.2	150	4.9	0.91	0.70
	VRC1	13	13	4.6	1500	2%	5.8	81%	56%	62%	56%	88	4.4	211	6.2	137	3.4	0.83	0.70
	VYN	75	75	10.0	7648	23%	28.7	42%	21%	18%	25%	90	3.1	187	3.2	123	4.3	0.78	0.55

Table 2. Summary of plot level data, cont.

Key to Table 2 columns:

- 1) In years, as of 2005
- 2) Years since logging or attack. TOD2 had evidence of multiple episodes.
- 3) Avg. height, m, green to red stems only, with DBH > 4cm
- 4) Stems / ha, all types, green to snag, > 4 cm DBH
- 5) Number of dead stems > 4 cm DBH / Total stems
- 6) Basal area in sq.m/ha, green to red stems only, with DBH > 4cm
- 7) Plot average gap fraction in 30 degree zenith angle from fisheye photos (2006)
- 8) Sky view factor in 2006
- 9) Radiation transmittance, 2006
- 10) Radiation transmittance, 2008
- 11) Peak SWE in mm
- 12) Maximum average ablation rate between sequential surveys, mm/day
- 13) Average ratio of peak SWE in plot to peak SWE in clearcut
- 14) Average ratio of ablation rate in plot to ablation rate in clearcut

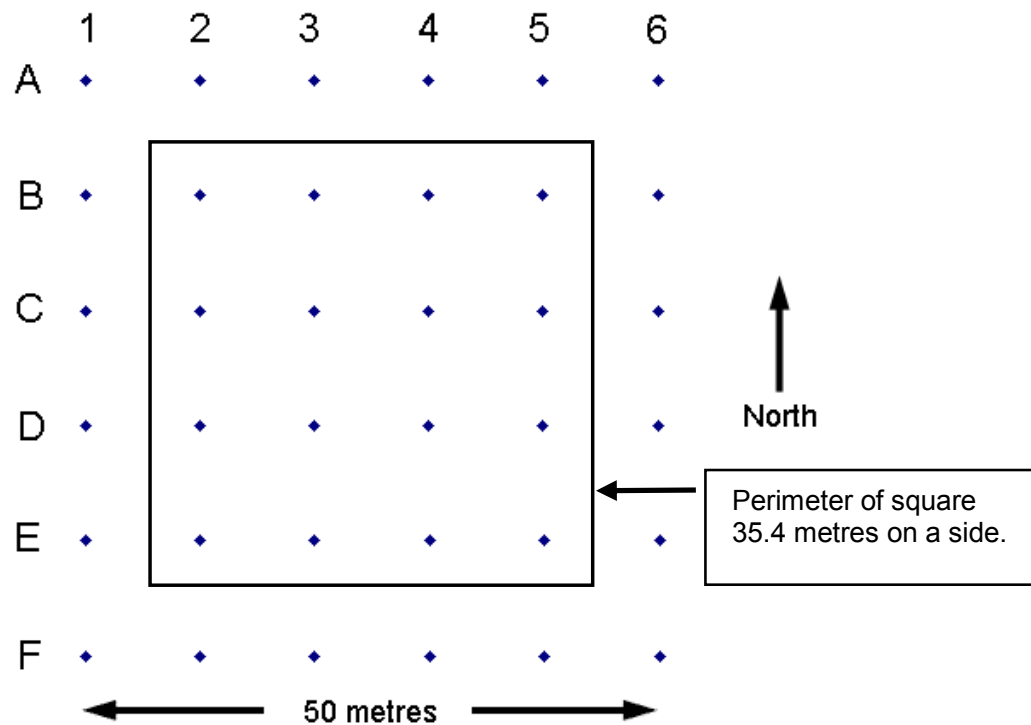


Figure 1. Line-intercept sampling design for coarse woody debris.

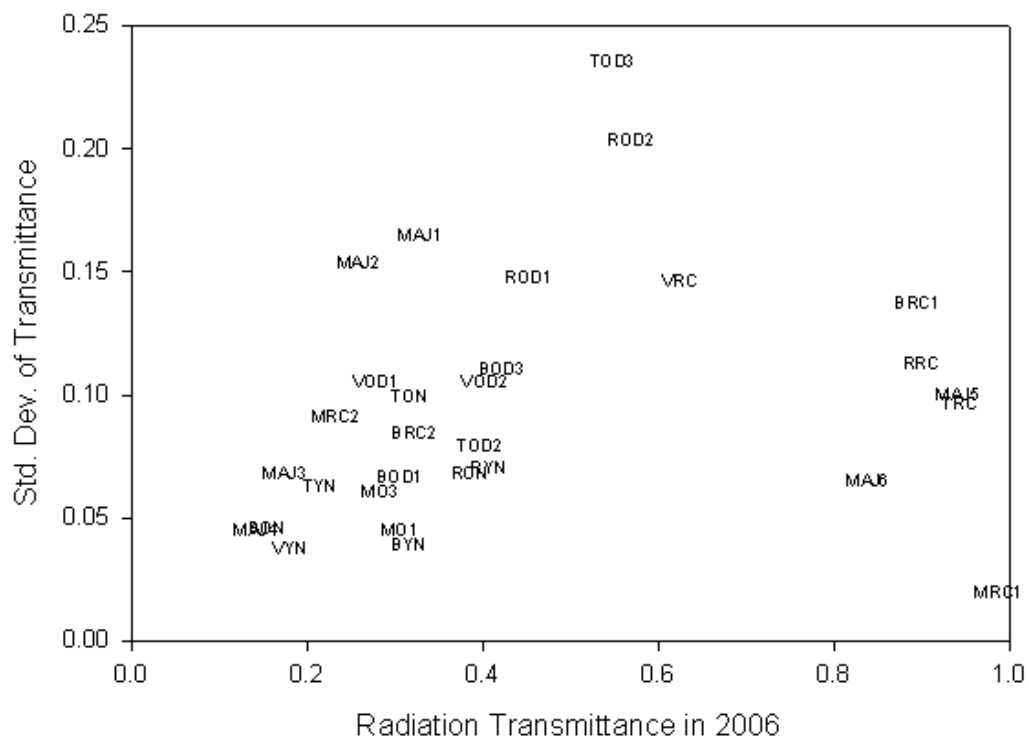


Figure 2. Standard deviation of transmittance versus average radiation transmittance.

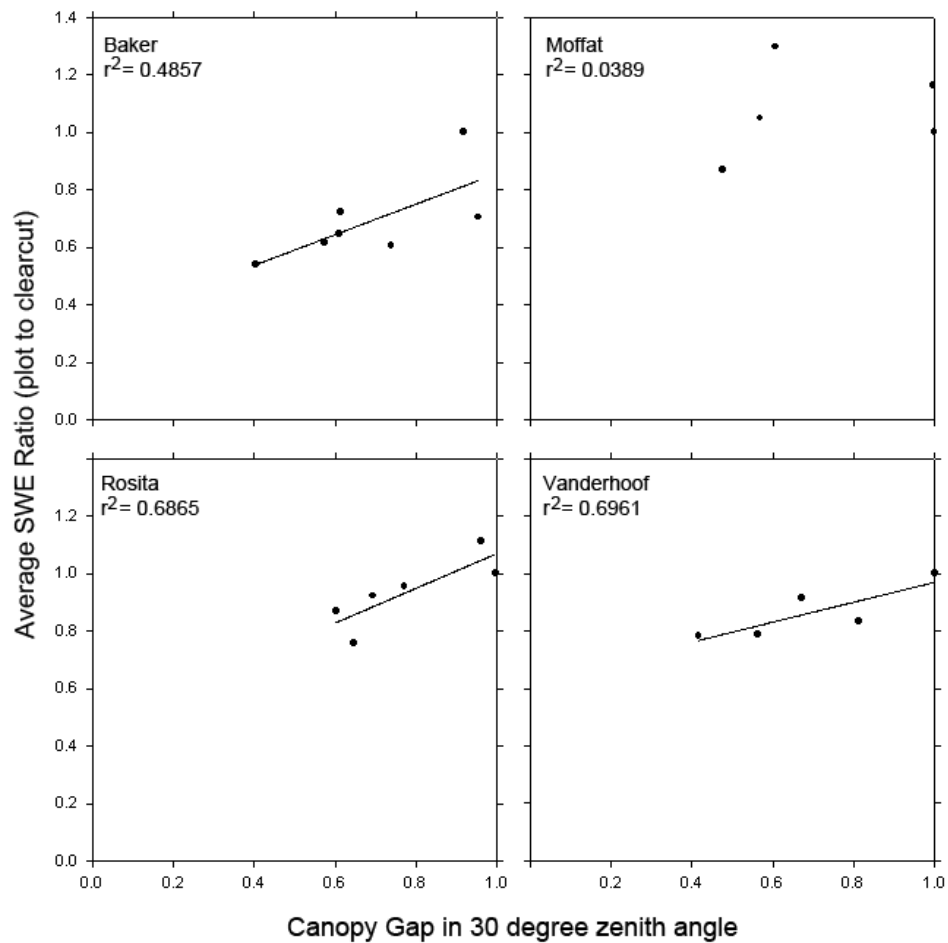


Figure 3. Average SWE ratios versus canopy gap in each study area

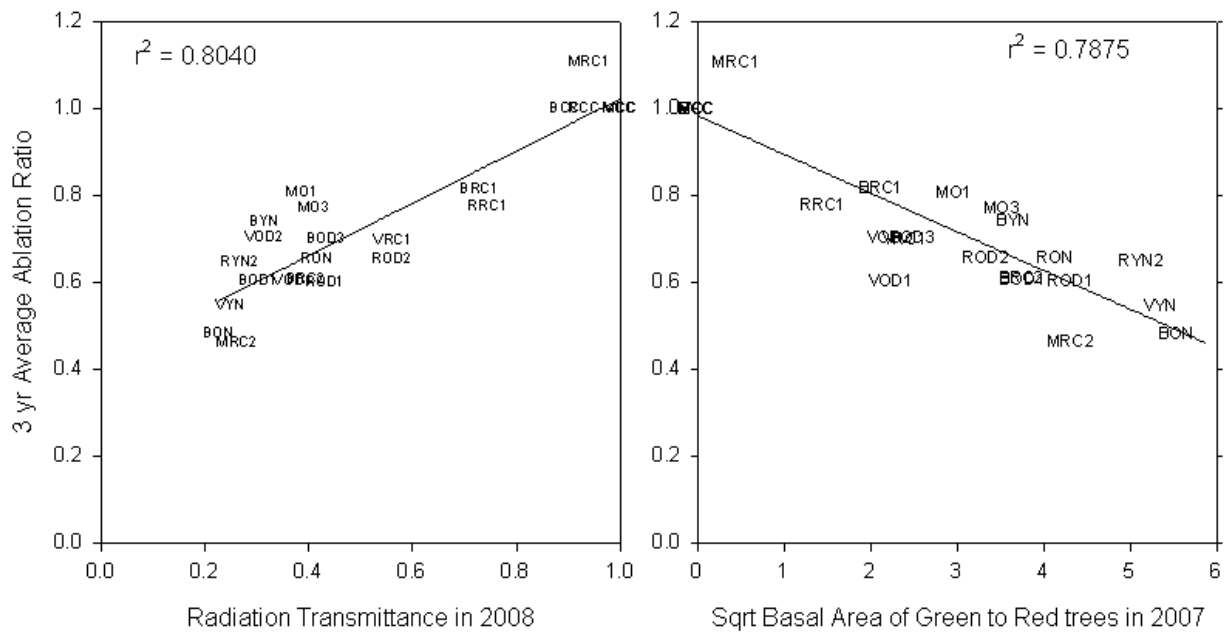


Figure 4. Average ablation ratios versus plot average radiation transmittance and square root of basal area.

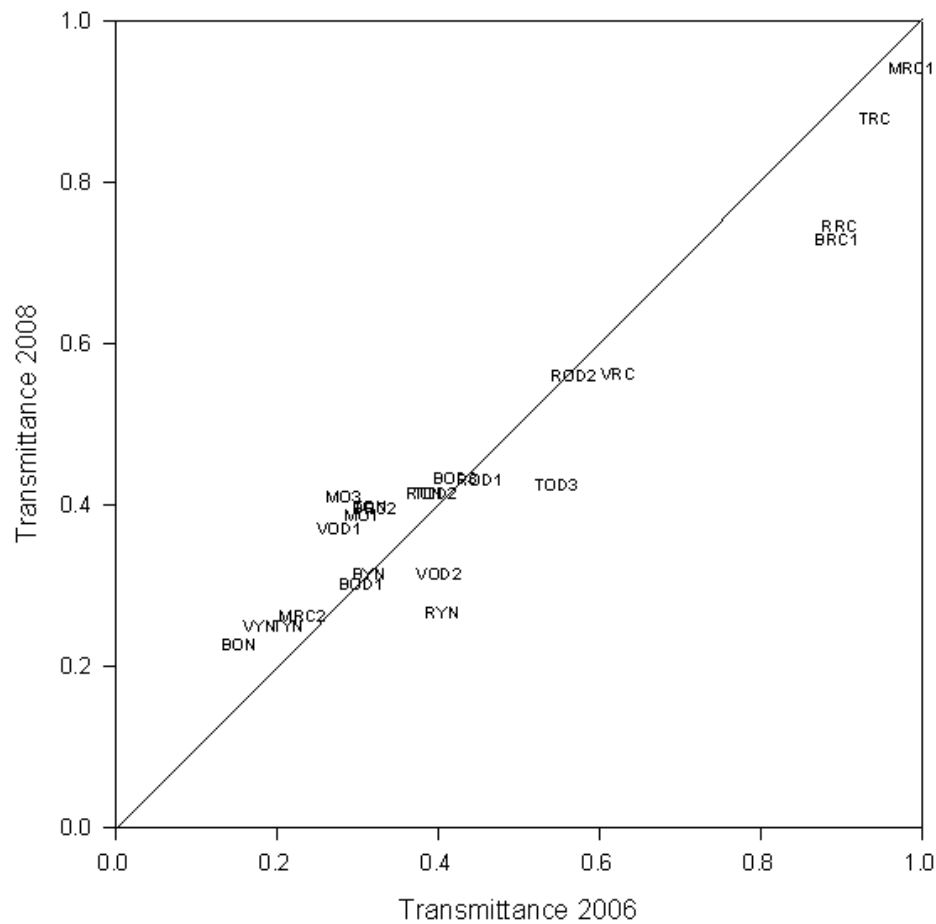


Figure 5. Plot average solar radiation transmittances in 2008 versus 2006.

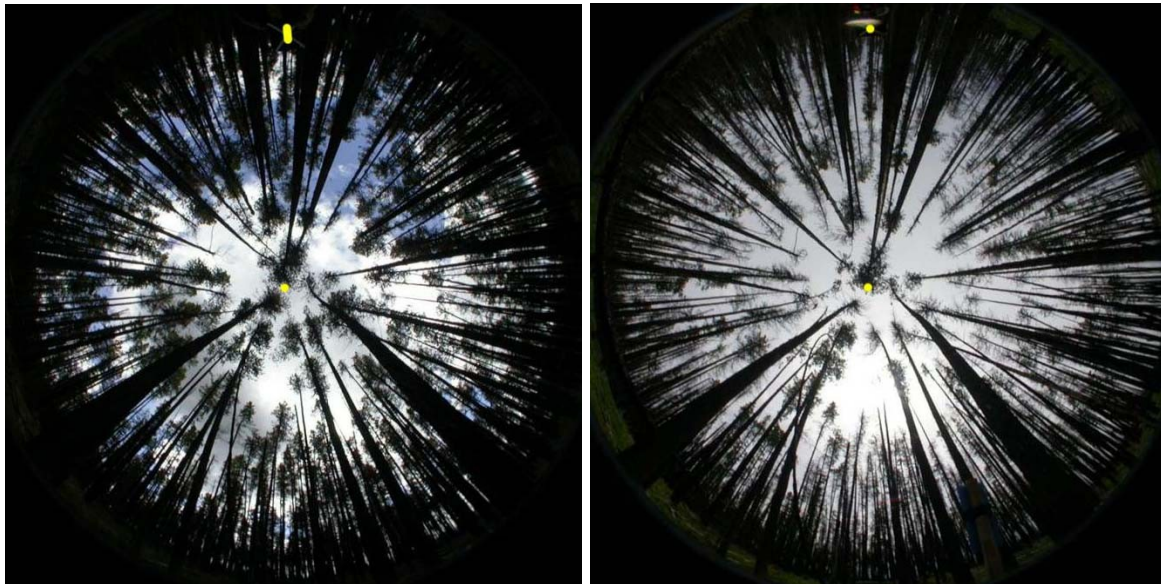


Figure 6. Hemispherical canopy photos taken at point B1 in plot MO1 in May 2006 and June 2008. This plot was beetle-attacked the summer of 2005 and at least 67% of the trees were defoliated by the time the second photo was taken. Radiation transmittances at this point were 35% and 41% in the two years while plot average transmittances were 31 and 39%.

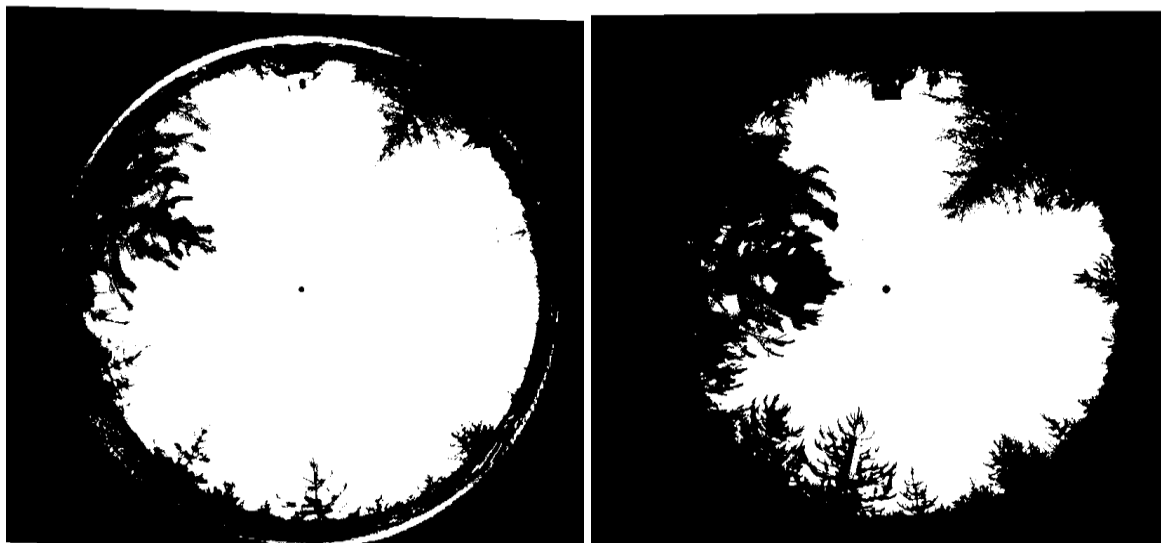


Figure 7. Hemispherical canopy photos taken at point C5 in plot BRC1 in 2006 and 2008. North is at the top. It is in a block that was logged between 1991 and 1997 and the average height of stems > 4 cm DBH in 2007 was 3.9 m. Plot average radiation transmittances in 2006 and 2008 were 90% and 73%.

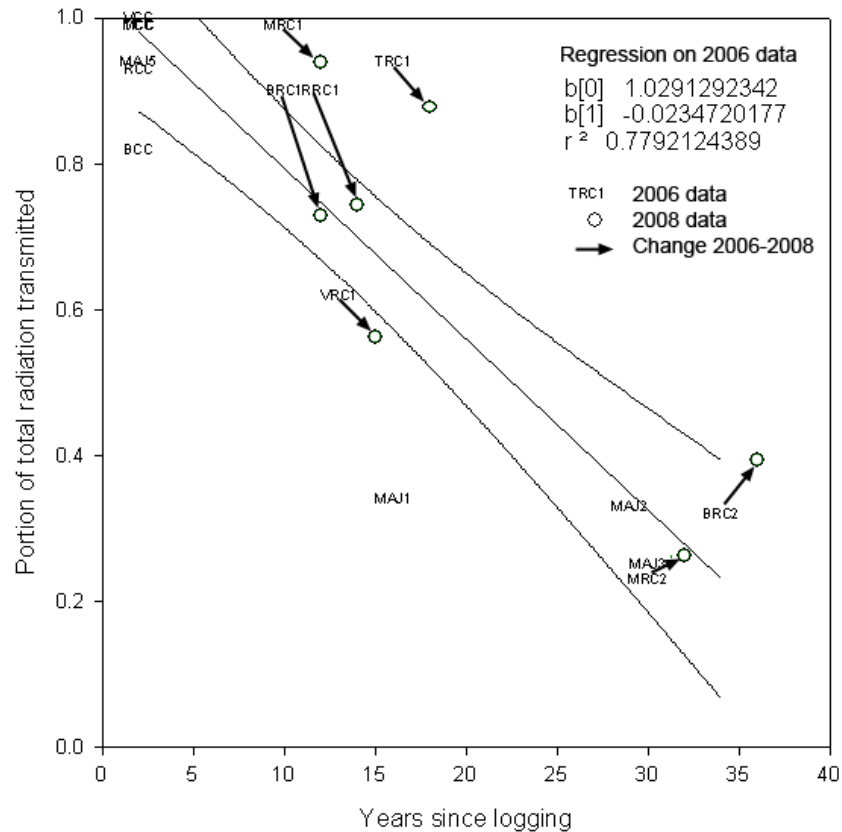


Figure 8. Radiation transmittances in plantations versus age in 2006 (indicated by plot abbreviations) and 2008 (open circles). Changes in plots that were re-photographed in 2008 are indicated by arrows.

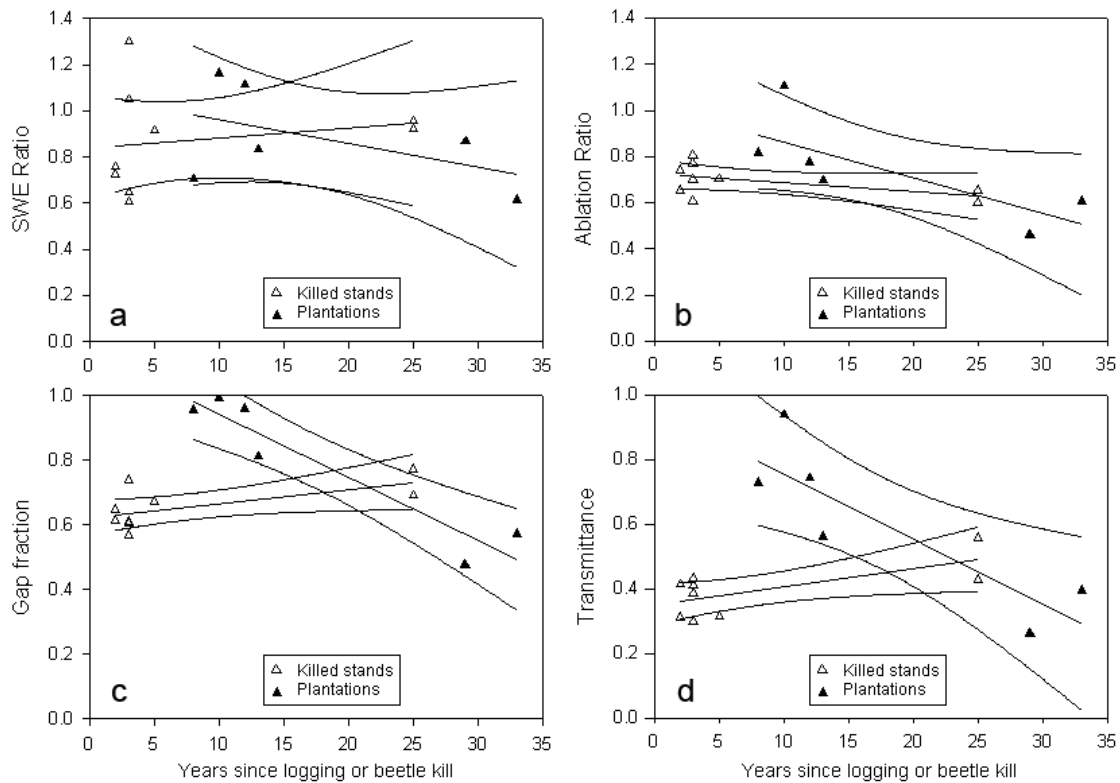


Figure 9. Plot average SWE ratios (a), ablation ratios (b), gap fractions (c), and solar radiation transmittances (d) versus time since logging or defoliation. Regression lines and 95% confidence intervals on regressions are shown.