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The Impact of Pine Beetle Infestation on Snow Accumulation and Melt

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THE IMPACT OF PINE BEETLE INFESTATION ON
SNOW ACCUMULATION AND MELT

by

EVAN T. PUGH

B.A., Haverford College, 2007

A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirement for the degree of
Doctor of Philosophy

Department of Geological Sciences

2012
This thesis entitled:
The Impact of Pine Beetle Infestation on Snow Accumulation and Melt
written by Evan T. Pugh
has been approved for the Department of Geological Sciences

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.
The mountain pine beetle is killing many trees in Colorado’s high-elevation forests. The thinned canopies found in impacted forests intercept less snow and transmit more radiation than canopies in living forests, altering snow accumulation and melt processes. Employing field studies and hydrologic modeling, I compared snow, forest, and meteorological properties beneath living and pine beetle-killed tree stands. By monitoring eight pairs of living and dead tree stands for two years, I observed the different hydrologic processes at work during different stages of tree mortality. During year one, all eight dead stands were in the red phase of tree death — the trees still retained needles. Snow accumulation was the same under living and red phase stands. However, snowmelt was more rapid in red phase stands, leading to advanced snowpack depletion. Solar transmission was not higher in red phase stands, suggesting faster melt and earlier depletion were caused by accelerated needle loss that lowered the albedo of the snow surface. By year two of the monitoring study, many of the dead trees had progressed to the needle-less grey phase of tree death. Snow accumulation in grey phase stands was 15% higher than in paired living stands. Snow in grey phase stands melted more rapidly than in living stands, likely as a result of increased canopy shortwave transmission. To
further investigate the effects of naturally thinned canopies on canopy snow interception, I made daily snow depth and density measurements in three living and two grey phase adjacent lodgepole pine stands for 45 days the following year. Dead stand snowpacks were both denser and deeper than those in living stands, characteristics attributable to diminished canopy snow interception. Over 10 storms, living and dead stands intercepted 41% and 18% of snowfall, respectively. Finally, to better understand the interplay between increased subcanopy snow accumulation and decreased solar shading in grey phase stands, I parameterized a widely-used hydrologic model for living and dead pine conditions in Colorado. Results suggest melt timing in these dead conditions is highly sensitive to the length of time snow remains in a tree canopy, where snow is more likely to sublimate.
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CHAPTER 1

INTRODUCTION

This dissertation comprises three main chapters. At the time of this writing, the first of these chapters (Ch. 2) has been published in Ecohydrology (Pugh and Small, 2011). Chapter 3 is in review at Hydrology Research (Pugh and Small, in review a) and Chapter 4 is in review at Hydrological Processes (Pugh and Small, in review b). These chapters are each works that stand on their own as well as in the larger context of this dissertation.

Chapter 2 describes my initial fieldwork comparing snow accumulation and melt in pairs of living and dead pine stands. Chapter 2 also introduces a conceptual model of snow process impacts following tree death. Chapter 3 elaborates on this work by testing the hypothesis that dead pine canopies intercept (and thus sublimate) less snow than living pines. Chapter 3 also discusses how much it is possible to improve land surface models by modifying snow interception schemes. Finally, Chapter 4 describes modeling exercises that illustrate the sensitivity of snow processes in a widely-used land surface model to small amounts of canopy reduction by applying the Canadian Land Surface Scheme 3.5 (CLASS) to local
meteorological measurements. Chapter 4 also investigates how these snow processes vary with precipitation magnitude and timing.
CHAPTER 2

MONITORING SNOW ACCUMULATION AND MELT IN LIVING AND DEAD FOREST SITE PAIRS

2.1 ABSTRACT

The mountain pine beetle is killing many trees in Colorado’s high-elevation forests. The thinned canopies found in dead tree stands should intercept less snow and transmit more radiation than canopies in living forests, altering snow accumulation and melt processes. We compare snow, forest, and meteorological properties beneath living and pine beetle-killed tree stands. Eight pairs of living and dead tree stands were monitored over two years along the headwaters of the Colorado River. During year one, all eight dead stands were in the red phase of tree death -- the trees still retained needles. Snow accumulation was the same under living and red phase stands, but snow melt was more rapid in red phase stands. As a result, the snowpack was depleted one week earlier in the red phase stands.

Canopy shortwave transmission was not higher in red phase stands. We hypothesize that the faster melt and earlier depletion in red phase stands was caused by accelerated needle loss which lowers the albedo of the snow surface. By year two, many of the dead trees had progressed to the needle-less grey phase of
tree death. Snow accumulation in grey phase stands was 15% higher than in paired living stands. Snow in grey phase stands melted more rapidly than in living stands, likely as a result of increased canopy shortwave transmission. We combine our results with those from previous studies to develop a conceptual model that describes how beetle infestation affects snow accumulation and melt in the different stages of mortality.

2.2 INTRODUCTION

The high-elevation forests that are a primary source for Colorado’s domestic and agricultural water needs are changing rapidly due to an infestation by the mountain pine beetle (MPB; *Dendroctonus ponderosae*) (*USFS*, 2010). MPB are native to Colorado’s high elevation forests. However, the severity of MPB infestation and resulting tree death has increased dramatically over the past 15 years. In Colorado, over 16,000 km² of Lodgepole (*Pinus contorta*) and Ponderosa Pine (*Pinus ponderosa*) forest have been infested by MPB since 1996 (*USFS*, 2011). It is predicted that the current epidemic will kill most of the pines in these areas. Current widespread MPB outbreaks are not limited to Colorado; they are also impacting forests in much of the Western US and British Columbia, Canada (*Ministry of Forestry and Range*, 2009). The cause of the current widespread MPB outbreaks across North America is unclear, but likely involves multiple factors that include climate change and past land management (*Logan et al.*, 2003; *Aukema et al.*, 2008; *Macias Fauria et al.*, 2009). This study is not focused on establishing the
causes of MPB infestation, but instead on quantifying the impacts of widespread tree death on snow accumulation and melt. Understanding the dynamics of mountain snowpack is critical for effective management of water resources in the Western US.

The current MPB infestation in Colorado’s headwaters is causing rapid changes in forest characteristics that will likely impact hydrologic processes. MPB are very destructive to forest canopies, often killing all of the mature trees within lodgepole pine stands (Schmid and Mata, 1996). Evergreen trees do not retain their needles indefinitely, but seasonally shed older, inner needle whorls. On average, healthy lodgepole pines retain needle cohorts for between 9 and 13 years, depending on forest elevation (Schoettle, 1990, 1994; Vose et al., 1994). MPB-infested trees lose their needles and woody biomass more rapidly than healthy trees. The process of MPB-induced tree death creates two distinct classes of dead trees. During the first two years following death, a lodgepole pine’s needles will change color to red and start falling off (Wulder et al., 2006). This stage of tree death is termed the “red phase”. Generally by the end of the third year after infestation, most of a dead lodgepole pine crown has been denuded of needles (Wulder et al., 2006). Trees that have been completely denuded of needles are in what is termed the “grey phase”.

MPB infestation affects forest characteristics that are known to impact the accumulation and ablation of snow, which in turn impact the water balance of entire drainage basins (Bales et al., 2006). Forest canopies create sheltered
subcanopy environments by attenuating the amount of incident solar radiation transmitted to the ground (Hardy et al., 2004; Link et al., 2004) and intercepting incoming precipitation (Golding & Swanson, 1978; Kattelmann et al., 1983; Musselman et al., 2008; Molotch et al., 2009; Veatch et al., 2009). Large portions of that intercepted precipitation sublimate back to the atmosphere (Pomeroy and Schmidt, 1993; Pomeroy and Gray, 1995; Hedstrom and Pomeroy, 1998). Relative to clearings, forests also experience reduced variability in subcanopy humidity and temperature through slower wind speeds (Benier, 1990), vegetation heat storage, and canopy longwave emission (Raynor, 1971; Rouse, 1984; Link and Marks, 1999; Pomeroy et al., 2009). Lower wind speeds and attenuated incoming shortwave radiation lead to slower snowpack ablation (Molotch et al., 2009). In snow-dominated regions, forest cover is the strongest predictor of both snow accumulation and ablation (Varhola et al., 2010).

To date, studies of the hydrological impacts of MPB infestation have largely been focused on the water yield from the basin. The effects on snow accumulation and melt have largely been ignored, with the exception of two studies completed in British Columbia (Boon, 2007, 2009). Long term water yield studies have shown increased runoff from MPB infested basins that rises to a maximum 15 years after the initial insect infestation (Love, 1955; Hibbert, 1965; Bethlahmy, 1974, 1975; Potts, 1984). Changes are still measurable in impacted basins 25 years after the outbreak. These types of studies do not provide a mechanistic understanding of how MPB infestations impact the hydrologic cycle. For example, the contributions
from modified snow accumulation and melt processes are not isolated from other
effects such as changes in evapotranspiration. Here, we measure how MPB
infestation impacts the dynamics of snow accumulation and melt. In addition, we
examine the differences in shortwave transmission and surface albedo between the
three tree mortality phases in order to better understand the observed changes in
snow dynamics.

The only previous studies of the effects of MPB infestation on snow water
equivalent (SWE) were completed using data from forests in British Columbia
(Boon, 2007, 2009). In both studies, the author measured snow accumulation and
ablation in a living stand, a dead stand, and a clearcut. In Boon (2007), 70% of the
dead trees were transitioning from the red phase to the grey phase of tree death.
The remaining 30% were in the grey phase. In the second study (Boon, 2009), trees
in the dead stand were all in the grey phase of death. Boon (2007, 2009) observed
more accumulation in the dead stand than in the living stand. This was interpreted
to be the result of reduced canopy interception of snow and subsequent sublimation.
In the second study, Boon (2009) observed accelerated dead stand ablation. This
was caused by increased shortwave radiation resulting from the thinning of the
forest canopy. The enhanced accumulation outweighed the faster melting, so the
net effect was prolonged snow cover duration under the dead stand.

Boon’s (2007, 2009) comparisons were complicated by the fact that forest
characteristics were different in the living and dead stands, including stand density,
trunk diameter, and canopy coverage. This complication is unavoidable because
severe MPB infestations kill all suitable host trees (Schmid and Mata, 1996). The trees in living stands are largely uninfested because they are different from those in the dead stands, in terms of age, species, or stand density. For example, in the current Colorado outbreak, only ponderosa pine trees with diameters < 20 cm are resistant to infestation (Negrón and Popp, 2004). As in Boon (2007, 2009), the living and infested stands monitored in our study did not have identical forest characteristics.

To study the effects of tree death on snow accumulation and melt, we measured snow properties, solar radiation, and tree stand characteristics along the headwaters of the Colorado River in central Colorado. Our study differs from Boon’s (2007, 2009) in three ways, and therefore provides new information about how MPB-infestation impacts snow hydrology. First, the climate, topography and forest characteristics are different at our Colorado study area. Second, we made measurements at eight pairs of living and infested forest stands, instead of a single living-infested stand pair as in Boon (2007, 2009). This allows us to quantify variability between sites and calculate statistics. Slope and aspect are similar within each site pair, yielding similar shortwave radiation at the top of the forest canopy. Third, the infested stands in our study area were in the red phase of tree death at the start of the observation period. In contrast, Boon compared grey phase stands with living stands. In the discussion, we combine our results with Boon’s to develop a conceptual model of how the effects of MPB-infestation on snow hydrology change throughout the sequence of forest death stages.
Most forest stands infested by MPB are composed of trees in various stages of death, as well as some living trees that are not infested (Klutsch et al., 2009). Similarly, nearby living stands typically include some infested trees. This complication was unavoidable in our study. In the first year of observation (2009), we identified eight site pairs with adjacent living and dead stands. The trees in the infested stands were in the red phase of the death progression. By the following year, the monitored stands provided a range of mortality comparisons because the infested stands progressed through the death stages at different rates. In addition, a significant number of trees in one of the living stands began to die. As a result, our statistical comparisons are strongest using data from the first year of observations. Our field observations were carried out in two years with different meteorological conditions, making comparisons between the two years difficult. In lieu of a decadal observational study on the effects of MPB on snow hydrology, we have chosen to present findings based on data collected during two field seasons. By combining our results with those from previous studies (Boon, 2007, 2009), we are able to formulate a conceptual model that can be tested in future field efforts.

2.3 METHODS

We studied eight living/dead site pairs in the subalpine headwaters of the Colorado River (Figure 2.1) during the winters of 2009 and 2010. Each site pair consisted of one 3600 m² living lodgepole pine or mixed conifer stand and one 3600
Figure 2.1. Site pair locations along the headwaters of the Colorado River in north central Colorado. Filled circles are living stands. Diamonds are dead stands.

m² dead lodgepole pine stand. Site pairs were initially identified and chosen based on topographic properties. Study stands range in elevation from 2680 meters above sea level (asl) to 2796 meters asl, and have east and west-facing slopes which range in steepness from 0.5° to 24.5° (Table 2.1). We allowed a maximum difference between the two stands in a site pair of 15 m for elevation, 10° for slope, 45° for aspect, and 200 m for distance apart. Most pairs were much more similar than the
| Site | Initial Mortality | Elevation (m) | Slope (deg) | Aspect (deg) | Forest Classification | Pine Composition (% stems) | Stem Density (stems/ha) | Mean Pine DBH (cm) | Basal Area (m²/ha) | Canopy Transmission | May 1st Rad (W/m²) |
|------|-------------------|---------------|-------------|--------------|-----------------------|---------------------------|------------------------|-------------------|------------------|-------------------|-----------------|------------------|
| 1    | Living            | 2722          | 14.8        | 248          | Mixed (E)             | 44.2%                     | 1776                   | 14.0±5.3*         | 27.3             | 0.49±0.40         | 5059            |
|      | Dead              | 2718          | 15.7        | 253          | Lodgepole             | 73.7%                     | 1791                   | 18.0±6.2          | 45.6             | 0.36±0.28         | 5040            |
| 2    | Living            | 2695          | 9.3         | 264          | Mixed (S)             | 12.1%                     | 2200                   | 12.7±7.9*         | 27.9             | 0.34±0.18         | 4968            |
|      | Dead              | 2680          | 2.9         | 256          | Lodgepole             | 87.0%                     | 2058                   | 17.4±6.2          | 48.9             | 0.43±0.29         | 5034            |
| 3    | Living            | 2692          | 5.6         | 264          | Mixed (L)             | 48.5%                     | 3237                   | 16.0±7.1*         | 65.1             | 0.74±0.43*        | 4953            |
|      | Dead              | 2690          | 2.5         | 262          | Lodgepole             | 83.8%                     | 1744                   | 20.7±7.8          | 58.7             | 0.18±0.06         | 4994            |
| 4    | Living            | 2725          | 14.8        | 285          | Lodgepole             | 94.6%                     | 4965                   | 11.3±4.2*         | 49.8             | 0.66±0.45*        | 4751            |
|      | Dead              | 2738          | 17.1        | 267          | Lodgepole             | 71.3%                     | 1587                   | 16.4±5.6          | 33.5             | 0.25±0.08         | 4826            |
| 5    | Living            | 2789          | 23.7        | 256          | Lodgepole             | 100%                      | 6191                   | 8.5±4.2*          | 35.1             | 0.89±0.30*        | 4733            |
|      | Dead              | 2796          | 24.5        | 257          | Lodgepole             | 100%                      | 1210                   | 18.7±5.6          | 33.2             | 0.64±0.34         | 4826            |
| 6    | Living            | 2719          | 4.3         | 88           | Lodgepole             | 92.8%                     | 2184                   | 13.1±6.6*         | 29.4             | 0.81±0.42*        | 4978            |
|      | Dead              | 2716          | 2.2         | 71           | Lodgepole             | 77.8%                     | 1131                   | 24.1±10.7         | 51.6             | 0.44±0.27         | 5000            |
| 7    | Living            | 2697          | 0.5         | 128          | Lodgepole             | 100%                      | 6254                   | 9.7±4.4*          | 46.2             | 0.13±0.01*        | 5005            |
|      | Dead              | 2699          | 1.2         | 122          | Lodgepole             | 100%                      | 786                    | 23.6±6.8          | 34.4             | 0.59±0.27         | 5025            |
| 8    | Living            | 2724          | 9.4         | 311          | Lodgepole             | 87.3%                     | 1116                   | 22.6±10.0         | 44.8             | 0.11±0.01*        | 4701            |
|      | Dead              | 2725          | 18.4        | 270          | Lodgepole             | 80.0%                     | 786                    | 19.5±11.4         | 23.5             | 0.22±0.02         | 4849            |

**Table 2.1.** Site Characteristics in 2009. Mixed forests are described by the dominant species present: L indicates lodgepole pine (*Pinus contorta*), E indicates Engelmann spruce (*Picea engelmannii*), and S indicates subalpine fir (*Abies lasiocarpa*). May 1st radiation is the total direct radiation hitting each site on May 1st modeled from a 10m DEM. * indicates a significant difference at p < 0.05
criteria for acceptable differences stipulated. A calculation of May 1 solar radiation was made to test site pair suitability. Above-canopy shortwave radiation was projected on respective slopes for each site pair and pair-differences were <2%. This calculation does not include differences in forest characteristics. In the first winter of observations, the dead stands were in the red phase of tree death. By the second year, the dead stands were in different stages (discussed in Results I).

In order to observe the study stands at various stages of death, we conducted a tree census at each stand measuring species dominance, tree trunk diameter at breast height (DBH), stem density, and tree mortality stage. Censuses were taken immediately following snowmelt in 2009 and 2010. The census area was demarcated by an octagon bounding line laid out with string (Figure 2.2). The octagon had a radius of 30 m from the central marked tree to the outer edge. Every tree within the perimeter was measured for species, DBH, mortality, and if applicable, stage of mortality. Stand species composition, stem density, and basal area were calculated from these field data.

We divided study stands into four classifications based on the extent of tree death. Finding completely alive or dead stands was not possible given constraints on site pair proximity and topographic characteristics. Living stands were defined as stands with less than 50% tree mortality. Initially, living stands ranged from 2.5% to 48% mortality, with an average of 19.9% tree mortality. A tree’s mortality was identified by the presence of red needles or total denudation. To classify dead tree stands, we used a percent grey phase relative to percent red phase ratio (G:R
Figure 2.2. Study stand sampling schema. Locations of measurements taken during the first expedition of the year are marked in black. Measurement locations for the subsequent expedition are in grey.

Red phase stands, red/grey transition stands, and grey phase stands were defined as stands with G:R ratios of less than 1, between 1 and 1.5, and greater than 1.5, respectively. Even though we use categories to describe different stages of mortality, we also analyzed snow and litter properties relative to continuous measures of stand mortality.

All sixteen stands were sampled between February and May of 2009 and January and May of 2010 for snowpack depth, density, and temperature. Locations of measurements within study stands can be seen in Figure 2.2. Monthly sampling occurred in January, February, and March; in April sampling frequency increased
to bimonthly in order to capture the signal of ablation. Radiation was measured in June of 2009 and 2010. Snow surface litter was measured on April 18, 2010. An albedo experiment was performed on April 27, 2010.

In order to measure snowpack density and temperature, a snowpit was excavated at each study stand. We measured snow density using a SnowMetrics 250 cc density cutter. On each subsequent field expedition, the location selected for the snowpit was rotated 45° radially around the central marked tree to avoid anthropogenic site contamination. The snowpit was dug five meters from the centrally marked tree. In 2009, we measured snowpack density at three depths in the snowpit in order to expedite measurements. Results from the three point measurement protocol were compared with results from continuous density measurements. Differences were less than 5%. In 2010, vertically-stratified measurements were made every 10 cm in the snowpit.

On each sampling trip, twelve snow depth measurements were taken at each stand. A snow probe was inserted into the snow at three locations at ten meter increments along four cardinally-oriented transects originating from the centrally marked tree. On subsequent field expeditions, the snow depth measurements were taken one meter farther from the transects to ensure undisturbed snow. SWE was then calculated using the depth-weighted snowpit density and the average plot snow depth (Boon et al., 2009). In early May of both years, snow cover was measured at each of the stands on three separate days. Snow cover was calculated
as the ratio of snow to bare ground found along each of the four snow depth transects.

The structure of the 2009 data permitted use of non-parametric Wilcoxon signed-rank tests to identify differences in snow properties between living and dead stands (Wilcoxon, 1945). The Wilcoxon signed rank paired test was used to analyze the 2009 data because it has fewer assumptions than comparable parametric tests. Nonetheless, a paired t-test yielded nearly identical results as the signed rank test. In 2010, we monitored three mortality comparison classes (e.g., living vs. grey phase). Therefore, we no longer had sufficient (~five) site pairs in each mortality comparison class to perform a meaningful paired statistical test, either parametric or non-parametric. Therefore, we compared SWE for each site pair individually, using t-tests. The twelve snow depth measurements from each site were first multiplied by the single snow density value from that site prior to the statistical test. We chose to compare SWE values between site pairs, rather than simply snow depth, so that results from 2010 could be compared to those from 2009. As discussed in the results, the density data from 2009 showed that there were no significant differences in density between living and red phase stands.

iButton temperature sensors were installed in snowpits at four of the site pairs (Maxim Integrated Products, 2009). At each of the stands in these site pairs, sensors were installed at depths of 12.5 cm, 37.5 cm, and 62.5 cm in the snowpit (roughly breaking the pit into thirds) to record continuous snowpack temperatures. The iButtons sensors were embedded 30 cm horizontally into the snowpit wall and
snowpits were backfilled following sensor installation to minimize cold wave penetration. Additional sensors were installed to measure air temperature at all site pairs.

In early June 2009 and 2010, Hukseflux LP02 pyranometers were used to directly measure the amount of solar radiation being transmitted through the canopies at all site pairs. At each stand, a mobile pyranometer was used to take twelve measurements at three evenly spaced locations along the snow depth transects originating from the centrally marked tree. Each radiation measurement was the average of 60 seconds at 1 second intervals. Pyranometer measurements were taken one meter above the ground. A second pyranometer, time synchronized with the mobile one, was mounted in a nearby clearing. Canopy transmission was calculated by dividing the subcanopy radiation measurement by the clearing radiation measurement. Since canopy shortwave transmission varies with solar zenith angle and diffuse skylight (Ni et al., 1997), measurements were made on clear, sunny days during the two hours surrounding the solar maximum. From 2009, we have cloud-free transmission data comparing living and red phase stands. From 2010, our cloud-free transmission data compares living and grey phase stands.

Hemispherical photos of the canopy were taken in November 2009 and 2010 at the same locations within each study stand as the transmission measurements. Photos were taken using a Nikon D700 camera with a Sigma EX Fisheye 8mm lens.
The camera was positioned one meter above the ground, leveled to gravity, and oriented to true north.

In mid-April 2010, we measured snow surface litter by photographing a 1 meter by 1 meter PVC pipe square placed on the snow surface. At every study stand, this PVC square was placed at four locations fifteen meters from the centrally marked tree (Figure 2.2).

We performed two albedo experiments at the end of April 2010. The goal was to quantify how snow albedo changes when pine needles are added to the surface. These experiments were based on the protocol of Melloh et al. (2001). Lodgepole pine needles are grouped in pairs of two. We added 400 lodgepole pine needle pairs to a 0.61 m radius circle of fresh snow in increments of 50 needle pairs. Each group of 50 needle pairs weighed roughly 3 g and the 400 needle pairs had a mean length of 5.1±1.1 cm. Needle pairs were placed uniformly within the circle area (Figure 2.3). Following each addition of more needle pairs, albedo was measured for 30 seconds from a height of 0.4 m with two LP02 pyranometers. The two pyranometers were mounted on a boom arm with one pointing up and one pointing down. Albedo was calculated as the ratio of incoming radiation reaching the downward-facing pyranometer. Additionally, a digital photo was taken of the circle of snow containing surface litter. This process took a total of fifteen minutes. The experiment was first performed in a clearing and then again ten minutes later in a lodgepole pine stand with a stem density of 2100 stems/ha. Before each experiment,
the two pyranometers were held side-by-side in direct sunlight to ensure correct calibration. Differences were less than 1%.

In addition to adding needle pairs to the snow during each experiment, we also measured the albedo after the addition of lodgepole twigs, a 0.6 m radius black circle, and a 0.6 m radius reflective circle. The same twigs were added to both the clearing and forest sites. The twigs were added to greatly increase the percent litter cover of the snow circles. The black circle and reflective circle were measured to reveal any difference between the clearing and forest sites. The black circle was made of matte black poster board and matte black gaffer’s tape. The reflective circle was made of reflective foil insulation with a bubble core. Forest albedo...
measurements of the black and reflective control circles were ~15% lower on average than similar measurements taken in a clearing. Lower albedo measurements in the forest are likely due to the presence of tree trunks in the pyranometers’ fields of view (i.e., the field of view extended beyond the experimental zone). The surrounding snow cover beyond the plan-view area of the experiment likely influenced the results.

The digital photos taken during the snow surface litter measurements and albedo experiments were analyzed to compute percent litter cover. This process consisted of converting the images to grayscale, orthorectifying the images in ESRI ArcGIS to preserve equal area between sequential photos, and finally, using the black and white threshold function in Adobe Photoshop to calculate the percentage of the image pixels that were litter and not snow. Images with high-contrast shadows were discarded.

In order to gauge years studied relative to long term records, data from SNOTEL site CO05J04S (Natural Resources Conservation Service (NRCS) National Water and Climate Center: SNOTEL Data Network–SNOTEL Data–All Sensors, 2010, available at http://www.wcc.nrcs.usda.gov/snotel/; hereinafter referred to as NRCS, 2010), which is in the same valley as the study site pairs, are reported. CO05J04S is 2.5 km from the nearest study site pair (Site 5). CO05J04S has an average annual (1986-2008) air temperature of 1.2 °C with an average monthly low of -15.3 °C in January (NRCS, 2010).
2.4 RESULTS I: PROGRESSION OF TREE DEATH AT STUDY STANDS

Following each winter of snow measurements, we conducted a tree census of the study stands. Lodgepole pine is the dominant species of tree (>70% stems) at most of the study stands (Table 2.1). Three of the living stands are composed of less than 50% lodgepole pine; these stands were classified as mixed conifer. The dominant tree species in these mixed conifer living stands are as follows: Engelmann Spruce (*Picea engelmannii*) at Site 1, Subalpine Fir (*Abies lasiocarpa*) at Site 2, Lodgepole Pine at Site 3.

Dead lodgepole stands had larger mean tree diameters than nearby living stands, but lower stem densities. The smallest trees with pitch tubes resulting from MPB attack had a DBH of 10 cm. In all but one site pair, the living stands had more stems per hectare than the dead stands against which they were compared (Table 2.2). The biggest difference was 6254 stems/ha living to 786 stems/ha dead at site pair 7. The extreme dissimilarity of stem densities at site pair 7 makes this pair an outlier. The one site pair that did not have more stems in the living stand had a similar number of stems in both living and dead areas (1776 stems/ha living to 1791 stems/ha dead at site pair 1). Stem density and DBH did not vary greatly between 2009 and 2010.

The mortality classifications of the different study stands changed between 2009 and 2010 (Figure 2.4). In 2009, all eight site pair comparisons were between living stands and red phase stands. By 2010, however, only two of those living vs. red phase site pairs remained. The others consisted of two living vs. transitional
<table>
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<th>Aspect (deg)</th>
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<th>% Diff DBH</th>
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Table 2.2. Site Comparison. Absolute values of differences between living and dead stand topographic descriptors. Percent difference (positive values are greater in the dead stand) of forest stand structure parameters and modeled incoming solar radiation between January and May 2009. All tree census data are from 2009.
Figure 2.4. 2009 and 2010 mortality classifications for each site calculated by taking the ratio of grey phase dead trees to red phase dead trees (G:R ratio). Living stands have less than 50% mortality. No G:R ratio is calculated for living sites.

site pairs, three living vs. grey phase site pairs, and one red phase vs. transitional site pair. Living stands had an average of 19.9% mortality in 2009 and 21.2% in 2010.

2.5 RESULTS II: SNOW AND RADIATION PROCESSES

From October 2008 to June 2009 (winter 2009), SNOTEL site CO05J04S recorded 50.5 cm of precipitation (NRCS, 2010). For the same time period in 2010, there was 46.7 cm of precipitation. Over the last 25 years (1984-2008), the average precipitation from October to June was 50.5 cm, with a minimum of 30.5 cm in 2002 and a maximum of 70.9 cm in 2003. The 25 year average April 1 SWE at the SNOTEL site is 35.5 cm and the standard deviation is 7 cm (NRCS, 2010). Total snow accumulation at SNOTEL site CO05J04S during the winter of 2009 was average relative to the previous 25 years. Winter 2010 had slightly below average snow accumulation. However, the 2010 snow year was anomalous in that most of the precipitation came in large late-spring storm events.
In 2009, the snowpack under living and red phase pine stand pairs became isothermal on the same date (Figure 2.5). There was an initial five-day period of isothermal snowpack beginning on March 18. After this interval, temperatures fell back below freezing before becoming isothermal for the remainder of the melt period on April 8. Similar amounts of snow had accumulated under living and red phase stands on the first three sampling dates: February 8, March 8, and April 5. The maximum SWE value recorded was 0.31 m at the living stand of site pair 8 on March 8. On this date, the minimum was 0.18 m at site pairs 3 (living) and 5 (dead). Once the snowpack became isothermal for the second time, the dead pine stands had significantly lower SWE totals than their living counterparts (Wilcoxon T(N = 8) = 18, p = .008). Once melt began, SWE was lower in the red phase stands because snow depth was lower than in the paired live stands. No consistent differences in snowpack density were observed between site pairs during the melt interval.

The percent snow cover under red phase pine stands was significantly lower than under living stands toward the end of the snow-covered period (Figure 2.6; Wilcoxon T(N=8) = 14, p = 0.016 on May 8, T(N=8) = 10.5, p = 0.031 on May 15). For example, on May 8, there was only 24% snow cover on average beneath dead stands but 68% on average under living stands. By May 15, all snow was gone from under dead stands, while an average of 5% snow cover remained under the living stands. Snow was gone from under red phase tree stands as much as one week sooner than under living stands.
Figure 2.5. Temperature and SWE records for Winter 2009. Snow beneath living and red phase dead stands became isothermal on the same date. The included 2009 SNOTEL SWE record is normalized to the 25 year (1984 – 2008) average maximum SWE. Error bars represent one standard deviation. * indicates significant differences at p < 0.05.

Analysis of hemispherical photos shows similar percent canopy openness within living/red phase site pairs. The canopy openness values for living and red phase stands varied from 22.4 to 30.9%. In general, stands with higher stem density had lower canopy openness. There was no significant difference in canopy openness between living and red phase stands within site pairs. The other measure of canopy transmission, direct measurement with pyranometers, showed no consistent
difference between living and red phase stands. Canopies at two of the eight site pairs, site pairs 1 & 2, transmitted similar amounts of sunlight. These two site pairs were mixed conifer (living) and lodgepole (red phase). Of the remaining six site pairs, the living stand canopies transmitted more sunlight at four stands (T-test, p < .01). Site pair 3, one of the four site pairs with more sunlight in the living stand, was mixed conifer (living) and lodgepole (red phase). The other three site pairs, site pairs 4 – 6, were made up of lodgepole (living) and lodgepole (red phase). In the two remaining site pairs, site pairs 7 and 8, the red phase stand canopies transmitted more sunlight (T-test, p < .01). Both site pairs were composed of living and red phase lodgepole stands.

By 2010, the canopies of three stands were nearly devoid of needles. Percent canopy openness in these grey phase stands ranged from 29.2 to 38.9% and was significantly higher than the living stands within site pairs (p<0.05). Direct measurements of transmission showed significantly more solar radiation arriving in
grey phase subcanopies than in their living counterparts (p<0.05). Within site pairs, grey phase canopies transmitted an average of 6.2% more solar radiation than living stands.

We now describe the time series of SWE observed in 2010 by comparison class. As discussed in the methods, the reduction in sample size due to differential progression of tree death required different statistical analyses than in 2009. Snow in red phase stands accumulated in similar amounts to the corresponding living stands. However, the snow in the red phase stands melted more rapidly (Figure 2.7a, p < 0.05 on Day of Year 121). This result is consistent with our findings from 2009, which were based solely on a comparison between red phase and living stands. This significant reduction in SWE under red phase trees occurred after a considerable litter layer had appeared on the snow surface. Next, we compare accumulation and melt for the two pairs of living and red/grey transition stands. No consistent differences in accumulation or melt were observed (Figure 2.7b). However, there was more accumulation at one of the red/grey stands at peak SWE. Finally, more snow accumulated under all three grey phase stands than under the corresponding living stands at peak SWE (Figure 2.7c, p < 0.05 at peak SWE). The differences varied from 11% to 21%. The greater accumulation in dead stands was still measurable soon after ablation began (Day of Year 107). However, SWE was lower in the grey phase stands than the living stands two weeks later (Day of Year 121). This dramatic reversal in relative SWE values shows that melt was nearly twice as rapid in the grey phase stands during the middle of the ablation period.
Figure 2.7. SWE record for Winter 2010 by mortality comparison class. T-tests were performed on each site pair. The included 2010 SNOTEL SWE record is normalized to the 25 year (1984 – 2008) average maximum SWE. Error bars represent the standard deviation in SWE values for each stand, calculated using a single snow density measurement from each stand. * indicates a significant difference at p < 0.05.

Snow surface litter varied with tree mortality stage (Figure 2.8). We represent surface litter as Litter Factor, defined as percent litter cover divided by stand basal area, to normalize for different stand structure. Significantly more total snow surface litter existed under red phase stands than under living stands (p < 0.05). When total surface litter is broken down into component parts, two additional trends are revealed. First, there are significantly more needles under
Figure 2.8. The amount of snow surface litter observed on April 18th, 2010 at multiple sites in various stages of tree death. Snow surface litter is broken into two component parts: needles and pinecones/branches/bark. Snow surface litter is represented as litter factor, which normalizes for study stand basal area. Within each litter component classifier, dissimilar letters represent a significant difference at p < 0.05. Error bars represent one standard deviation.

red phase stands than under living stands (p < 0.05). Second, there are significantly more pinecones/branches/bark under grey phase stands than under living or red/grey transitional stands (p < 0.05). The highest percentages of litter cover observed were ~20% and occurred under red phase tree stands. Snow surface albedo varied with increasing litter cover in a clearing and in a forest (Figure 2.9). Linear regressions of the two datasets yielded significant negative correlation: clearing (r² = 0.75, p < 0.01) and forest (r² = 0.61, p < 0.01). In the discussion, we use this relationship to estimate differences in albedo between living and dead stands.
2.6 DISCUSSION

Our measurements of shortwave transmission through the canopy show no consistent differences between living and red phase stands. However, the inherent spatial variability and heterogeneous nature of canopy gaps complicate efforts to compare in-situ measurements of canopy transmission between two different tree stands. Further complications may arise because stands do not entirely consist of trees in the same phase of mortality. Intuitively, red phase stands may transmit more radiation for two reasons. First, red phase stands appear to have predominantly downward-facing whorl orientation, which may reduce the solar shading capabilities of dead trees (Ni et al., 1997). Second, as shown in the results by our surface litter measurements, red phase trees lose needles more rapidly than living trees. This needle loss should result in more pathways for sunlight to pass
through red phase canopies. Although confounded by variability and spatial heterogeneity associated with canopy gaps, any differences that do exist in canopy transmission between living and red phase stands are likely not large or would have been apparent in the measurements. In 2010, because most needles were gone from the grey phase canopies, the differences in canopy transmission between living and grey phase stands were large enough to observe. On average, grey phase stands allowed 6.2% more solar radiation through their canopies.

If the amount of solar radiation reaching the snowpack beneath living and red phase stands is similar, there must be another process driving earlier snowmelt under red phase stands. We hypothesize that the earlier snowmelt in red phase stands, compared to living stands, was caused by greater litter fall and the resulting decrease in snow surface albedo. Throughout the winter, needles and branches fall as litter into the snowpack. As melt proceeds, the litter that was distributed throughout the snowpack is concentrated at the surface lowering the snow’s albedo (Winkler et al., 2010; Pomeroy and Dion, 1996; Hardy et al., 1998; Melloh et al., 2001, 2002). During the melt interval, there was 50% more litter at the surface in red phase stands. This is expected given that red phase trees lose all their needles in two to three years, compared to 9-13 years for needle turnover in healthy trees (Schoettle, 1990, 1994; Vose et al., 1994). Compared to living stands, the higher litter concentration in red phase stands (Figure 2.8) should yield lower surface albedo and greater absorption of radiation at the snow surface. We did not directly measure differences in snow surface albedo between the different mortality classes.
On average, albedo should be lower by 5% in the red phase stands, using the slope of the curve in Figure 2.9 and observed differences in litter cover (Figure 2.8). At midday in May, this would yield a ~30 W m\(^{-2}\) increase in absorbed radiation, using the mean of our measured transmission values (0.45). The maximum observed litter cover in red phase stands was 20%, which would yield an even greater albedo change of ~25%. These calculations do not consider local aspect and slope (i.e., irradiance).

Our results from the comparison of grey phase and living stands (2010 data) are largely consistent with Boon’s (2009) findings. First, there is more accumulation in grey phase stands relative to comparable living stands. Second, melt is more rapid in grey phase stands. There is one notable difference. At the Colorado sites, the increase in melt rate was great enough such that SWE was lower in grey phase stands toward the end of the snow-covered period. In contrast, there was more snow in the grey phase stands throughout the melt period at the British Columbia site (Boon, 2009). There are several reasons why this difference could exist, including (1) magnitude and timing of snow accumulation during the year data were collected; (2) timing within the MPB death progression; and (3) stand characteristics and topography.

We propose the following conceptual model for MPB effects on snow accumulation and melt. It is based on results presented here and by Boon (2007, 2009). This model differs from discussions elsewhere (Boon, 2007, 2009; Potts, 1984) because it explicitly accounts for differences in processes between stands in
the red and grey phases of tree death. Although we have divided the mortality stages into red and grey phases, intermediate conditions exist and are important. In addition, stand characteristics continue to change during the grey phase, as trees fall over and the understory regenerates. Even though it is simple, the model is useful for (1) guiding measurements of stand-level hydrological processes; and (2) making predictions of the effects of tree death on hydrographs.

During the red phase, trees have not yet lost significant amounts of canopy material. Therefore, there are no measurable changes in canopy snow interception or subcanopy snow accumulation at this point in the death progression. In addition, since many needles remain in the red phase canopy, any increase in transmitted shortwave radiation is negligible. Because transpiration has ceased in red phase trees, they likely retain less water than living trees. Therefore, longwave absorption and re-emission may also be smaller in the dead stands (Rouse, 1984). As a result of changes to longwave retention and emission, there may be a small advance in the date that the snowpack becomes isothermal. However, this advance was not observed here. An important difference was observed to exist during the ablation period. The rate of needle fall is several times faster in dead stands, yielding lower snow albedo and absorption of more radiation by the snowpack. The result is faster snowmelt in red phase stands. Canopy snow interception and subcanopy accumulation are not altered during the red phase of tree death. Therefore, the net input of water from snowmelt to the soil system is unchanged.
In the grey phase, more snow accumulates under dead stands than living stands because less snow is intercepted by the thinned, needle-less canopy. In addition, the thinned canopy allows for the transmission of more solar radiation to the forest floor. This leads to more rapid snowmelt in dead stands. The greater transmission of solar radiation in dead stands could also advance (1) the date the snowpack becomes isothermal and/or (2) the depletion date. Whether or not this happens depends on various hydrometeorological factors, as shown by differences between our results and Boon’s (2009). The snow surface albedo is higher beneath grey phase stands, compared to living stands, because the canopy is no longer shedding needles. This albedo change would counteract the increased solar transmission and could be important in some environments (e.g., shaded slopes). The relative timing of snow depletion under grey phase and living stands depends upon the combined effects of more SWE from reduced interception versus faster melt from more transmitted radiation. Regardless of changes in melt timing, there will be more snow accumulation and less interception loss via sublimation in grey phase stands. The result is an increase in the net input of water from snowmelt to the soil system.

The magnitude of snow accumulation changes in grey phase stands, compared to living stands, was different in our study and Boon’s (2009). Boon measured 74% more SWE under grey phase stands (Boon, 2007). This observation was made during a season with unusually large SWE (159% of normal). Differences in accumulation were smaller in the following year, during which accumulation was
closer to average (Boon, 2009). Our data from 2010 was measured during a winter season with below average snow accumulation. We observed additional snow accumulation in grey phase stands ranging from 11% to 21%.

The impact that increased accumulation in grey phase stands would have on streamflow is difficult to predict. Among other processes, streamflow would vary with reductions in stand evapotranspiration (Yang, 1998) and soil infiltration regimes. Additionally, it is unclear how changes in soil hydraulic conductivity associated with tree death would alter subsurface water retention, an important pre-stream hydrologic flow path in mountainous regions (Bonell, 1993). Predicting changes to impacted watershed hydrographs is outside the scope of this study.

2.7 CONCLUSIONS

We have presented a two year study comparing snowpack dynamics across a range of tree mortality stages. Results indicate that snow accumulation was similar under living and red phase stands, and was roughly 15% greater under grey phase stands. We observed no measurable difference in canopy shortwave transmission or percent canopy openness between living and red phase stands. Grey phase stands, however, consistently exhibited higher canopy transmission and percent canopy openness than living stands, with an average increase in transmission of 6% in dead stands. Significantly higher levels of surface litter were observed under red phase stands than under living stands. We demonstrated a strong negative linear correlation between forest litter and snow surface albedo using a simple albedo
experiment. Snowpack depletion was one week earlier beneath red phase stands as a result of reduced snow surface albedo. Grey phase stands also experienced advanced ablation, likely as a result of increased canopy solar transmission. In the snowmelt-dominated regions of the Western US, mountain snowpack is the largest input term in the mass balance equation that must be solved to calculate streamflow. The observed increase in snow accumulation caused by advanced tree death would yield more water from annual snowmelt.
CHAPTER 3

DETERMINING THE IMPACT OF TREE DEATH ON
STAND-SCALE CANOPY SNOW INTERCEPTION

3.1 ABSTRACT

Bark beetles have killed more than 100,000 km² of pine forest in western North America, causing trees to lose the majority of their canopy material and potentially leading to enhanced subcanopy snow accumulation. Over a 45-day period, we tested this hypothesis by measuring daily snow accumulation in three living and two dead lodgepole pine stands and in three adjacent clearings. The largest clearing was selected as our reference clearing based on previous studies. At maximum pre-melt snow water equivalent (SWE), this clearing had accumulated 50.4 cm SWE, while 45.6 cm SWE accumulated under dead stands and 38.1 cm SWE accumulated under living stands. Dead stand snowpacks were both denser and deeper than those in living stands. We attribute higher subcanopy accumulation under dead stands, compared to living stands, to diminished canopy snow interception and sublimation. Storm-scale canopy interception was also estimated by comparing SWE in forests and clearings before and after storm events. Over 10 storms, dead and living stands intercepted 18% and 41% of snowfall,
respectively. The amount of interception increased linearly with storm size in the living stands, but not dead stands. We estimate that more than half of snow falling on living stands sublimated, with measurably less sublimation in dead stands.

3.2 INTRODUCTION

Snow that falls on a needleleaf forest either passes through the canopy to the ground or is intercepted by the canopy on needles, branches, or bark (Hedstrom and Pomeroy, 1998). The magnitude of intercepted snow impacts the water budget because this snow is more likely to sublimate than subcanopy snow. Compared to snow on the ground, intercepted snow is more likely to sublimate because the forest canopy experiences greater wind speeds (Bernier, 1990; Raynor, 1971). In addition, the forest canopy has a lower albedo (~0.15) than the snow-covered ground (Pomeroy and Dion, 1996). Low canopy albedo persists with snow present on trees because intercepted snow is usually thin and translucent (Ni and Woodcock, 2000). The sublimated portion of intercepted snow is water that does not contribute to snowmelt. The magnitude of canopy snow interception depends on local climactic factors such as air temperature, wind speed, and precipitation (Pomeroy and Essery, 1999; Pomeroy et al., 1998; Schmidt et al., 1998) as well as forest structure characteristics such as canopy density and canopy height (Varhola et al., 2010; Veatch et al., 2009; Winkler and Moore, 2006). Forest structure can be drastically and rapidly altered by forest disturbance, such as insect attack, wildfire, and
blowdown. This study examines the impact that altered forest characteristics wrought by beetle infestation have on canopy snow interception.

The mountain pine beetle (*Dendroctonus ponderosae*; MPB) is currently impacting more than 100,000 km² of predominantly lodgepole pine (*Pinus contorta*) forest in western North America (MFR, 2011; USFS, 2011). During the first two years following infestation, pine needles turn reddish-brown and begin to fall off dead trees. This stage of mortality is called the “red phase” (Wulder et al., 2006). Increased needlefall can reduce snow surface albedo under the canopy and advance snowmelt (Pugh and Small, 2011). Within three years of the initial attack, the pines have been completely denuded of needles and the trees appear grey. The thinner canopies transmit more sunlight and are expected to intercept less snowfall (Boon, 2009; Pugh and Small, 2011). This needle-less stage of tree death is termed the “grey phase” (Wulder et al., 2006). During the grey phase, pine twigs and branches are sloughed (Klutsch et al., 2009; Teste et al., 2011), leading to even greater canopy thinning.

Beetle-induced tree death impacts hydrologic processes including evapotranspiration, soil infiltration, and snow accumulation and melt (Boon, 2009; Pugh and Small, 2011). Because forest canopy characteristics control snow interception, which in turn affects subcanopy snow accumulation, reductions in canopy density have important implications for snow accumulation on the forest floor (Molotch et al., 2009; Varhola et al., 2010; Veatch et al., 2009). Tree death drastically reduces available interception platforms. In previous studies it was
hypothesized that this will lead to greater subcanopy snow accumulation under dead trees, compared to pre-infestation conditions (Boon, 2007, 2012; Pugh and Small, 2011). In this study, we test this hypothesis using data collected from living and dead forest stands and adjacent clearings.

Previous studies have employed various techniques to measure canopy snow interception, at both the tree- and stand-scales. A widely-used method for measuring canopy interception on an individual tree is to weigh intercepted snow on real and artificial trees or branches. This method is also useful for measuring snow mass lost to sublimation and unloading (Hedstrom and Pomeroy, 1998; Montesi et al., 2004; Schmidt, 1991; Schmidt and Gluns, 1991). Further, snow interception has been studied by observing branch deflection following snow storms (Bründl et al., 1999; Schmidt and Pomeroy, 1990). To estimate intercepted load, these deflection measurements are compared to species deflection constants determined experimentally.

While tree-scale measurements are helpful for understanding the mechanics of interception processes, deployment of these techniques at the stand- or watershed-scale is not practical. To study interception at larger scales, subcanopy snow accumulation is compared to clearing snow accumulation resulting from individual storms. Measured canopy-clearing differences are then attributed to interception during the storm (McNay et al., 1988; Musselman et al., 2008; Storck et al., 2002). This approach is based on the assumption that the forested areas and clearings receive the same amount of precipitation. We used this method to
estimate interception. We measured snow accumulation in living and grey phase dead lodgepole pine stands as well as in adjacent clearings of varying area. The ratio of snow accumulation in forested areas relative to accumulation in adjacent clearings has been found to depend on clearing size (Golding and Swanson, 1978). Therefore our estimates of intercepted snow are sensitive to the size of the clearing we use as a reference for snowfall totals. This is discussed further in the site description (see Section 3.2: Study Sites and Methods).

Because interception reduces the amount of snow that accumulates under forests, it is integral to many hydrologic and land surface models. Hedstrom and Pomeroy (1998) developed an interception model that predicts interception using effective leaf area index ($LAI'$), species-specific snow loading coefficient ($S_p$), snowfall density ($\rho_{sf}$), and storm size ($P$). This model is widely used (e.g., Gelfan et al., 2004) and has been incorporated into several hydrologic and land surface models (e.g., CLASS, NOAH-MP). A key concept in the model is that the percentage of incoming snowfall intercepted by a canopy is inversely proportional to storm size. The amount of snow stored in the canopy asymptotes at a maximum intercepted load determined by characteristics of both the canopy and the intercepted snow. In the discussion, we identify how the effects of tree death could be better represented in snow interception models.

This study quantifies how conifer death impacts interception at the stand scale. Pugh and Small (2011) studied subcanopy accumulation beneath living and dead stands in multiple stages of tree death and did not observe additional
accumulation under red phase trees, which retain most of their needles. However, MPB snow studies (Boon, 2007, 2012; Pugh and Small, 2011) have reported higher snow water equivalent (SWE) under grey phase canopies than under adjacent living stands. Boon (2007) reported 75% more snow under grey phase stands during a year of extraordinary snowfall (159% of average). Other results (Boon, 2012; Pugh and Small, 2011), from years with closer-to-average snowfall, indicate more modest increases in grey phase stand snow accumulation, ranging from 3% - 21%. Here we clarify how the canopy snow interception process responds to stand-scale tree death by addressing three questions: 1) On a storm-by-storm basis, do living stands intercept more snow than dead stands?; 2), If so, is sub-canopy SWE lower under living stands?, and 3) Does more canopy sublimation occur in living stands compared to dead stands?

In the next section, we describe our study sites and experimental methods. Section 3.3 contains results from the 2011 snow accumulation field study. In Section 3.4, we discuss potential reasons for different magnitudes of snow accumulation in living and dead stands and suggest specific changes to improve interception modeling.

3.3 STUDY SITES AND METHODS

3.3.1 STUDY SITES

Our goal was to observe snow interception and accumulation processes in living and grey phase stands. During the winter of 2011, we studied five lodgepole
pine stands and three forest clearings in the subalpine headwaters of the Colorado River in north central Colorado (Figure 3.1; Table 3.1). Study sites ranged in elevation from 2693 m above sea level (asl) to 2699 m asl and were effectively flat, with slopes ranging from 0° to 0.5°. The maximum distance between any two site centers was 238 m (between Sites 3 and 8). Within each stand, a 2450 m² experimental zone was demarcated and sampled during the study. Each stand was composed of more than 95% lodgepole pine. The stands were classified based on the percentage of trees in the grey phase. The two grey stands selected had 69% and 83% trees in the grey phase (Table 3.1). The three other forested stands had less than 4% of trees in the grey phase. We refer to these non-grey stands as ‘living stands’, even though up to 41% of the trees in the stands are in the red phase of tree death (Table 3.1). Red phase trees are dead but still retain a significant majority of their needles, and thus affect interception and radiation in a similar fashion to living trees (Pugh and Small, 2011).

Previous studies comparing snow processes in living and MPB-impacted stands were complicated by the fact that forest characteristics were different in the living and dead stands, including stand density, trunk diameter, and canopy coverage (Boon, 2007, 2009; Pugh and Small, 2011). This complication is unavoidable because severe MPB infestations may kill the majority of suitable host trees (Schmid and Mata, 1996). The trees in living stands are largely uninfested because they differ from those in the dead stands in terms of age, species composition, or stand density. As in previous studies, we faced the same challenge
<table>
<thead>
<tr>
<th>Site #</th>
<th>Designation</th>
<th>Area m²</th>
<th>Basal Area m²/ha</th>
<th>Tree Height m</th>
<th>DBH cm</th>
<th>Stem Density stems/ha</th>
<th>Mortality % of stems</th>
<th>% Grey Phase</th>
<th>Canopy Density</th>
<th>Canopy LAI' m² m⁻²</th>
</tr>
</thead>
<tbody>
<tr>
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<td>360</td>
<td>•</td>
<td>•</td>
<td>•</td>
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</tr>
<tr>
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<td>•</td>
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<td>•</td>
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<td>•</td>
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<td>•</td>
</tr>
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<td>Living</td>
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<td>45.3</td>
<td>19.3</td>
<td>15.4</td>
<td>2432</td>
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<td>3%</td>
<td>71.7%</td>
<td>1.28</td>
</tr>
<tr>
<td>5</td>
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<td>2450</td>
<td>40.4</td>
<td>19.2</td>
<td>10.6</td>
<td>4618</td>
<td>35%</td>
<td>6%</td>
<td>71.4%</td>
<td>1.15</td>
</tr>
<tr>
<td>6</td>
<td>Living</td>
<td>2450</td>
<td>43.6</td>
<td>18.3</td>
<td>14.5</td>
<td>2642</td>
<td>41%</td>
<td>4%</td>
<td>72.6%</td>
<td>1.18</td>
</tr>
<tr>
<td>7</td>
<td>Grey Phase</td>
<td>2450</td>
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<td>19.3</td>
<td>18.3</td>
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<td>87%</td>
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</tr>
<tr>
<td>8</td>
<td>Grey Phase</td>
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<td>20.8</td>
<td>17.9</td>
<td>1746</td>
<td>69%</td>
<td>69%</td>
<td>57.8%</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 3.1. Site characteristics measured in April 2011. Additionally, all sites were between 2693 and 2699 m above sea level, had flat topography, and were composed of more than 95% lodgepole pine (*Pinus contorta*). Tree height and stem diameter at breast height (DBH) are stand averages calculated from tree census data. Canopy density and effective leaf area index (LAI') values are stand averages calculated from hemispherical photos.
Figure 3.1. Site locations along the headwaters of the Colorado River in north-central Colorado. Circle markers represent living stands, diamonds represent gray phase dead stands, and clearing sites are boxed in dashed lines. Shaded areas surrounding stand markers represent stand-scale experimental zones. During the study period, wind direction was predominantly from the southwest (73% of the time).

when choosing study sites. The living and impacted stands in our study were very similar with respect to basal area and tree height. However, the living stands had lower diameter at breast height (DBH) and higher stem density (Table 3.1). The effects of these differences in forest structure are evaluated in the discussion.

In addition to observing five pine stands, we took measurements in three nearby forest clearings that varied in size: 360 m² (Site 1), 800 m² (Site 2), and 2500 m² (Site 3). Golding and Swanson (1978) measured snow accumulation in a variety of cut clearings that varied in size. Clearings with a width of two times tree height accumulated the most snow, relative to nearby treed areas. When computing canopy snow interception as the difference between subcanopy accumulation and clearing accumulation, interception magnitude will vary depending on the clearing size that is used as reference. In her study investigating snow accumulation processes following beetle infestation, Boon (2012) used a 2500 m² reference clearing size. We
adopt the same reference clearing size (Site 3) to allow for comparable forest-to-open (F:O) snow-accumulation ratios. We compare snow accumulation in the three study clearings to relationships derived in previous studies to assess the suitability of the reference clearing (e.g., Golding and Swanson, 1978). The size of the reference clearing only affects the absolute magnitude of calculated canopy interception. The differences in snow accumulation between living and dead stands reported below are independent of the reference clearing used.

3.3.2 FIELD SNOW MEASUREMENTS

Regular measurements of snow depth, snow density, and snow and air temperatures were made at the eight study sites between 1 March and 15 April 2011. Daily, pre-storm, and post-storm snow depth measurements were taken. The timing of pre- and post-storm snow depth measurements was guided by snowfall predictions from NOAA hourly weather forecasts (NWSFO, 2011), which accurately predicted the beginning and end of storms. On each sampling trip, 28 snow-depth samples were taken at each study site with measurements every five meters along four 35-m long, cardinally-oriented transects. This design yields 224 measurements per survey (Pugh and Small, 2011).

The 28 snow depths from each site were combined with a single measurement of snowpack density from the same site to calculate stand-scale SWE. Snowpack density at each site was measured in a snowpit with a 250 cc SnowMetrics density cutter. Average snowpit density was calculated from measurements made every 10
Density measurements were taken every two days at new locations within each site.

Snowpack and air temperatures were measured every two hours at each site using iButton temperature sensors (Maxim, 2009). Snow temperatures were taken using sensors that were stratified throughout the snowpack at heights of 33, 66, and 100 cm above the soil. Air temperature was measured 2 m above the ground surface. All iButton temperature sensors were calibrated against a CS500 temperature sensor for two weeks prior to deployment. Wind speed and direction were measured at a weather station 7 km south of the study sites. Wind measurements were taken every 15 minutes from a height of 2 m using an RM Young 05103 wind monitor. Predominant wind direction was calculated from this data set. During storms, wind commonly (89% of the time) came out of the southwest and almost always exceeded 1 m s⁻¹ (96% of the time).

Hemispherical photos were taken of the forest canopy in August 2011 at the same locations within each study site as snow depth measurements. Photos were acquired using a Nikon D700 camera with a Sigma EX Fisheye 8 mm lens. The camera was positioned 1 m above the ground, leveled to gravity, and oriented to true north. The hemispherical photos were analyzed to calculate percent canopy openness and \( \text{LAI}' \) using the Gap Light Analyzer 2.0 software (GLA; Frazer et al., 1999). \( \text{LAI}' \) is defined as the product of a foliage clumping factor (Nilson, 1971) and the leaf area index (Black et al., 1991) and is a measure of total plant area, including both leaves and woody material. Canopy density is calculated from these
data by subtracting percent canopy openness from complete (100%) canopy cover. Reported $LAI'$ was integrated over the zenith angles 0° to 60° (Stenberg et al., 1994). Average $LAI'$ values for living and grey phase stands are 1.20 and 0.80, respectively. These values are consistent with regional estimates of $LAI'$ in living and grey phase lodgepole pine stands (Pugh and Gordon, 2012).

### 3.3.3 SEASONAL ACCUMULATION TRENDS

Differences in SWE between forest sites and the reference clearing represent SWE lost up to a given date due to the effects of the forest canopy on interception and sublimation (Storck et al., 2002). SWE Loss is calculated as

$$\text{SWE Loss} = \text{SWE}_{\text{clearing}} - \text{SWE}_{\text{forest}},$$

where $\text{SWE}$ is stand-scale snow water equivalent calculated from mean stand snow depth and snowpack density. We only completed this analysis for the accumulation period, after which the effects of melt and interception cannot be separated.

### 3.3.4 INTERCEPTION EVENT CALCULATIONS

We estimate interception during individual storms by measuring snow depth before and directly after storms. These mean stand snow depths were combined with the most recent snowpack density measurement (within 1 day) to calculate stand SWE. The SWE intercepted by the forest canopy (living or dead) is assumed
to equal the difference in new snow accumulation between forested stands and the reference clearing:

\[ I = \Delta SWE_{\text{clearing}} - \Delta SWE_{\text{forest}} \]  

(3.2)

where \( I \) is intercepted SWE and \( \Delta SWE \) is the change in snow water equivalent during the storm event. Storms during which mean air temperatures rose above -3° C were excluded to ensure that storms with rainfall did not obfuscate the analysis. Analyses were performed on all stands individually and for averages by mortality class. Both stand and class analyses yielded very similar results. In all figures, results are reported as class averages.

3.4 RESULTS

Snow depth and density surveys were completed daily over a 45 day interval from March 1 through April 15. In the reference clearing, SWE increased from 33.0 cm to 51.3 cm during this interval. This represents approximately 35% of total accumulation during the entire snow season. The snowpack temperatures in clearings and under grey phase stands became isothermal at 0° C for 6 days on 17 March (Day of Year (DoY) = 76). The snowpack then refroze before returning to 0° C on 2 April. The initial period of isothermal snowpack did not occur under living stands. Instead, living stand snowpacks became isothermal later, reaching 0° C for the first time on 3 April and staying isothermal for the remainder of the study period (Figure 3.2). The first precipitation event that was primarily rain occurred
on April 2nd and 3rd. Given the isothermal conditions and rainfall at this time, we define the end of the pre-melt period as April 3, and report maximum pre-melt SWE on this date. SWE increased monotonically prior to this date. After this date, snow events were interspersed with periods of melt and rainstorms.

The magnitude of snow accumulation in the three study clearings varied with clearing size, as expected given the results of Golding and Swanson (1978). For Sites 1-3, clearing width-to-tree-height ratios were 0.86, 1.73, and 3.76, respectively. At maximum pre-melt SWE, the reference clearing (Site 3) had accumulated 50.4 cm SWE. Pre-melt maximum SWE at the 0.86H clearing (Site 1) was 11% less than
at the 3.76H reference clearing (Site 3). The 1.73H clearing (Site 2) accumulated 17% more snow than the reference clearing. The differences observed throughout the accumulation period were similar to those measured at maximum pre-melt SWE.

Compared to the reference clearing, there was less snow accumulation on the ground beneath both dead and living forest stands. At maximum pre-melt SWE, dead and living pine stands had SWE of 45.6 and 38.1 cm, respectively, compared to 50.4 cm in the reference clearing. Therefore, dead stands accumulated 7.5 cm more subcanopy SWE than living stands. Both snow depth and density were lower in the living stands than in the reference clearing. In contrast, snow density in the dead stands equaled that in the clearing, but snow depths were lower (Figure 3.3). Differences in stand-scale SWE between living and dead stands are the result of both differences in snowpack density and depth (Figure 3.3 inset). The observed differences in depth, density and SWE between the mortality classes were consistent, on a percentage basis, throughout the observation period, not just at the time of maximum pre-melt SWE (Figure 3.3).

SWE Loss was greater under living stands than under dead stands. At maximum pre-melt SWE, living stand SWE Loss was 12.3 cm, while dead stand SWE Loss was 4.7 cm. These SWE Loss values represent 24% and 9% of the reference clearing snow accumulation, for living and dead stands, respectively. SWE Loss values from our study sites are similar to forest:open (F:O) SWE ratios reported in other studies (Table 3.2). SWE Loss in both living and dead stands
increased throughout the accumulation period (Figure 3.3), thus the F:O ratio remained relatively constant (not shown).

We measured snow depth prior to and immediately after storm events to estimate the magnitude of canopy interception. From 3 March to 27 March (DoY 62 – 88), there were 10 snowfall events during which air temperatures did not exceed -3° C. These storms yielded 18.2 cm of new SWE accumulation. Individual snowfall events lasted from 7 hours to 35 hours (Figure 3.2). Storm size (in SWE) in the reference clearing ranged from 0.3 cm to 5.1 cm, spanning the range expected for
Table 3.2. Forest-to-open clearing SWE ratios (F:O) at maximum pre-melt accumulation from recent MPB snow accumulation studies as well as from this effort. Winkler & Boon (2009) presented a synthesis of many unpublished results and, as such, a range of applicable means are presented from that data set.

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Living F:O Ratio</th>
<th>Grey Phase F:O Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spittlehouse (2006)</td>
<td>British Columbia, Canada</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Winkler &amp; Boon (2009)</td>
<td>British Columbia, Canada</td>
<td>0.74 – 0.78</td>
<td>0.84 – 0.89</td>
</tr>
<tr>
<td>Bewley, et al. (2010)</td>
<td>British Columbia, Canada</td>
<td>0.84; 0.98</td>
<td></td>
</tr>
<tr>
<td>Boon (2012)</td>
<td>British Columbia, Canada</td>
<td>0.73; 0.80</td>
<td>0.75; 0.94</td>
</tr>
<tr>
<td>This Study</td>
<td>Colorado, USA</td>
<td>0.76</td>
<td>0.91</td>
</tr>
</tbody>
</table>

On a storm-by-storm basis, SWE increased more in the reference clearing than in both living and dead stands (Figure 3.4a). The differences between each forested area and the clearing were consistent across storm size, on a percentage basis. Under dead stands, the increase in SWE was 86% of that in the reference clearing ($r^2=0.97$). The difference was greater in the living stands, where SWE only increased by 64% as much as that observed in the clearing ($r^2=0.89$). Therefore, the increase in SWE during storms was greater in the dead stands than in the living stands. Additionally, for two small storms (< 1 cm SWE) where living stands showed decreases in subcanopy “accumulation” (i.e., effectively intercepted 100% of incoming precipitation), dead stands had positive subcanopy accumulation.
Figure 3.4. A) Subcanopy snowfall SWE graphed versus snowfall SWE measured in the reference clearing (i.e., storm size). Subcanopy snowfall SWE is significantly correlated with clearing snowfall SWE for both living (y=0.64x; p<0.0001; r²=0.89) and dead stands (y=0.86x; p<0.0001; r²=0.97). Fit lines suggest that significantly more snowfall accumulated under dead than living stands. B) Intercepted SWE graphed versus change in reference clearing SWE. Intercepted SWE is significantly correlated with storm SWE for living (p<0.001; r²=0.40) stands, but not dead stands (p=0.175; r²=0.02). Error bars represent one standard deviation of SWE values calculated from stand snow depths. Dashed lines are an average of maximum observed interception values (Living=1.35 cm; Dead=0.56 cm). Regressions were performed with the assumption that when there is no clearing accumulation there can be no subcanopy accumulation (i.e., forcing the y-intercept of linear regression lines through the origin).

For each storm, we calculated intercepted SWE according to equation 3.2.

Simply summed over the storms, there was 18.2 cm of precipitation in the reference clearing. We measured 7.5 cm of interception in the living stands, and 3.2 cm in the dead stands. This is 41% and 18%, respectively; or a mortality-associated decrease
of more than half of the interception. Interception SWE significantly varied with storm size in living stands ($r^2=0.40$), but not in dead stands ($r^2=0.02$), as expected given Figure 3.4b. During the two smallest storms, the change in SWE on the ground was negative, equivalent to negative accumulation according to equation 3.2. In these cases, interception in the living stand was assumed to equal the accumulation amount in the clearing. Together, these storms accounted for < 1.0 cm of the total intercepted SWE. If instead we assumed zero interception in the living stands for these two storms, the total percent interception would be 35% instead of 41%. Values of interception (e.g., 41% in living stands) are not equal to 100% minus the slope of the best fit lines between subcanopy accumulation and clearing accumulation (Figure 3.4a) because those regressions include error associated with measurements in a natural system.

In order to compare our snowpack SWE record with our measurements of snowfall accumulation, we again limit the analysis period to the interval between DoY 62 - 88. This interval included 10 of the 11 cold storms observed during the 45-day study and occurred before snowmelt. During this 26 day period, SWE increased by 11.4 cm in the reference clearing, compared to ~19 cm of accumulation measured during the storms. Measured cold storm accumulation values are increased by 5% to account for accumulation during warm storms (see above). This difference between snowpack SWE increase (DoY 62 – 88) and accumulation during storms suggests that 40% of the precipitation reaching the reference clearing sublimated. Living stand SWE increased by 5.4 cm and dead by 10.3 cm during the same interval,
suggesting that 72% of precipitation falling on living stands sublimated and 46% sublimated in dead stands.

Because we made our post-storm measurements immediately following storms, we do not know how much of the intercepted snow was unloaded mechanically. As such, we cannot quantify the portions of total sublimation that are due to sublimation in the canopy as opposed to the ground. However, when looking at the sign (+/-) of SWE Loss during storms versus non-storm intervals (Figure 3.5), it appears the majority of SWE Loss occurred during storms. Negative SWE Loss, or apparent snow accumulation relative to the reference clearing, could result from either canopy snow unloading or snow sublimation in the clearing. Since most of this negative SWE Loss occurred without actual additional accumulation in the forest, it is likely due to sublimation in the clearing. Positive SWE Loss that is coincident with precipitation events suggests that the majority of sublimation in our forest stands occurred from canopy snow.

3.5 DISCUSSION

At maximum pre-melt SWE, dead and living pine stands had accumulated 45.6 and 38.1 cm SWE, respectively. This represents 91% and 76% of accumulation in the reference clearing. This difference between dead and living stands likely results from dissimilar canopy snow interception during individual precipitation events. During the interval DoY 62 – 88, dead and living pine canopies intercepted 18% and 41% of incoming snowfall, respectively. Through a comparison of season-
Figure 3.5. Water fluxes during the interval DoY 62 – DoY 88. A) Storm accumulation and SWE Loss in living stands. B) Water mass balance in living stands, represented as cm SWE. C) Storm accumulation and SWE Loss in dead stands. D) Water mass balance in dead stands, represented as cm SWE. P indicates precipitation, I indicates interception, U indicates unloading, and S indicates sublimation.

and storm-scale subcanopy snow accumulation, we estimated 46% of snow falling on dead stands sublimated and 72% of snow falling on living stands sublimated.

The sublimation of intercepted snow can be substantial, with up to 40% of the annual snowfall sublimating from conifers canopies (Hedstrom and Pomeroy, 1998; Lundberg et al., 2004; Pomeroy and Gray, 1995; Troendle and Meiman, 1986). This statistic refers to the percentage of snowfall that was intercepted by the canopy and later sublimated. As mentioned in the results, we were unable to partition our
estimates of snow sublimation into canopy and ground components. For the interval DoY 62 – 88, our estimates of total sublimation (i.e., from both the ground and the canopy) are 72%, 46%, and 40% for living stands, dead stands, and the reference clearing, respectively. Our measurements are very indirect and are only suggestive, based only on SWE changes on the ground. These values need to be confirmed via more direct measurements from eddy covariance or similar methods. Because SWE Loss was largely coincident with precipitation, we estimate that the majority of the sublimation that took place in the living stands occurred from intercepted canopy snow. This assessment agrees with the findings of studies conducted in both maritime and continental climates, which suggest that the majority of snow sublimation from conifer forests occurs from the canopy rather than from the ground (Molotch et al., 2007; Storck et al., 2002).

Our analyses are dependent on assumptions that introduce uncertainty to these results. We assumed that the observed differences in snow accumulation were the result of tree death, not simply an artifact of differences that existed between the stands prior to MPB infestation (Pugh and Small, 2011). Given the limited topographic variations across the study area, differences in slope, aspect, and microclimate are negligible between the sites. However, the dead stands studied did have larger diameter trees and lower stem densities (Table 3.1), consistent with the preference of MPB for infesting larger trees (Klutsch et al., 2009). Therefore, some of the measured differences in snow accumulation are likely due to stand
structure and canopy characteristics that existed prior to tree death (Woods et al., 2006).

Decreased interception in dead stands is likely the result of both reductions in the amount of canopy material and changes in the branch-scale mechanisms of interception and subsequent sloughing. At the stand-scale, the magnitude of subcanopy snow accumulation is inversely related to canopy cover (Varhola et al., 2010), presumably due to the effects of canopy material on snow interception. It follows that a reduction in canopy material in dead pine stands should yield reduced interception and greater snow accumulation on the ground. LAI′ in the grey phase stands is 0.81 whereas LAI′ in the living stands is 1.20. Therefore, approximately one third of the canopy material that could intercept snow has been shed from grey phase stands. If the amount of canopy material was the only control on interception, we would expect that interception was lower in dead stands by a similar magnitude. However, over the 10 snow-only events during the analysis period, the total amount of interception was 7.5 cm SWE in living stands and 3.2 cm SWE in dead stands (Figure 3.5). This is a larger change that one would predict from changes in LAI′ alone.

A reduction in overall tree canopy cover does not completely represent the changes in canopy conditions in dead pine stands. Branches on dead pines can hold smaller snow loads than living branches because of mortality-driven transformations in flexibility, shape, and needle-cover. By the time dead lodgepole pines enter the grey phase, branches are less flexible than living branches, leading
to accelerated sloughing of snow from twigs and branches (Klutsch et al., 2009; Teste et al., 2011). A substantial portion of this sloughing occurs during storms. Therefore, snow could be intercepted and temporarily held by the canopy, but fall to the ground prior to our post-storm measurements. Branches that do remain on grey phase trees are bent downward (Figure 3.6). This increases the bedding angle of intercepted snow, which enhances sloughing even more. The removal of needles and twigs on branches will increase the mean branch diameter. This reduces snow bridging and decreases snow load holding capability (Pfister and Schneebeli, 1999; Schmidt and Pomeroy, 1990; Schmidt and Gluns, 1991). Finally, the thinner canopies in grey phase stands should be subjected to higher wind speeds than canopies in living stands (Tarboton and Luce, 1997; Hellström, 2000). Unloading of intercepted snow should be more rapid in grey phase stands due to higher wind speed within the canopy.

The way that canopy processes are represented in commonly-used interception models is likely insufficient to predict changes associated with beetle-induced conifer death. Simple models scale interception with canopy cover (Hellström, 2000). Our $LAI'$ and interception data show that this approach underestimates the changes in interception resulting from tree death. More complex models predict interception using $LAI'$ in conjunction with parameters that represent snow loading capacity and branch morphology. For example, the Hedstrom and Pomeroy (1998) model also uses a species-specific snow loading coefficient ($S_p$), canopy plan area ($C_p$), and an unloading coefficient ($U$). These types
Figure 3.6. Diagram and images illustrating relevant changes to lodgepole pine branch and canopy following pine beetle infestation. A) Branch shape and deflection commonly observed in living and gray phase dead lodgepole pine found in north central Colorado. B) Hemispherical photograph of a living lodgepole pine stand with an $LAI'$ value of 1.29. C) Hemispherical photograph of a gray phase dead lodgepole pine stand with an $LAI'$ value of 0.73. The dead stand has a similar basal area to the living stand shown above.
of models can more adequately represent changes associated with tree death, if data exist to constrain parameters values. The Hedstrom and Pomeroy (1998) model incorporates a term for branch snow load capacity, $S_p$, which represents the maximum snow load per unit of branch area for a given tree species. For this term, Schmidt and Gluns (1991) suggest a value of 6.6 kg m$^{-2}$ for pines. Assuming this value is appropriate for the living stands observed here, we suggest lower values for $S_p$ would accurately represent maximum dead-branch snow loads. The maximum value of dead canopy snow load we observed in 2011 (Figure 3.4b) was roughly half of that observed in living canopies.

Modifications should also be made to the model terms for canopy plan area ($C_p$) and unloading rate ($U$). If snow fell vertically on a forest, the canopy leaf area available for interception ($C_p$) would equal the area of the top of the forest canopy, which is roughly equivalent to canopy density. Hedstrom and Pomeroy (1998) suggested that mature forest stands with wind speeds greater than 1 m s$^{-1}$ should have a $C_p$ value of 100%. This is because horizontal wind speeds would provide falling snow with diagonal trajectories capable of reaching all potential canopy area, including those areas below the upper canopy. However, in a grey phase stand, the probability of a snowflake hitting a branch should be lower, because most branches are devoid of needles and twigs. Thus, for a given wind speed, snowflake-branch contact is less likely in a dead stand than a living stand. Furthermore, a reduction in $C_p$ also decreases the predictive ability of $LAI'$. For canopies with $C_p$ values less than 100%, such as grey phase stands, $LAI'$ becomes a weaker predictor of
interception efficiency (Hedstrom and Pomeroy, 1998). The intercepted snow unloading coefficient \( U \) is another parameter that should be modified following tree death. As described above, \( U \) is likely larger and more rapid in grey phase stands due to faster average canopy wind speeds, downward-bending branches, and the increased likelihood of branch-breakage under snow loads.

3.6 CONCLUSIONS

Grey phase lodgepole pine stands intercept more than 50% less snow than living stands. Canopy interception is significantly correlated with storm magnitude in living stands, as predicted from earlier studies, but not in dead stands. In addition to reduced leaf area, this diminished capacity to intercept snow is likely due to a combination of other forest structure changes including modifications to branch morphology and flexibility. Because less snow is intercepted in dead canopies, substantially less snow is removed by snow sublimation. This decrease in sublimation losses led to 20% more subcanopy snow accumulation over the course of a season. We suggest that both the simple and more complex models commonly used to predict canopy snow interception are likely inadequate to model the interception of snow in dead stands like those studied here. Models that explicitly account for interactions between different scales of interception platform (e.g., needles, twigs, branches), branch orientation and flexibility, total plant area, and the top-of-canopy energy balance may be necessary.
CHAPTER 4

MODELING SNOW ACCUMULATION AND MELT
IN LIVING AND DEAD FORESTS

4.1 ABSTRACT

This study examines the effect of widespread forest disturbance wrought by the Mountain Pine Beetle (MPB; *Dendroctonus ponderosae*) on stand-scale snow accumulation and melt processes. We adjusted select parameters in the physically-based Canadian Land Surface Scheme 3.5 (*CLASS*) model to better understand processes leading to changes in water and energy cycles by simulating wintertime hydrology in living forest conditions and four sets of grey phase (*i.e.*, needleless) dead forest conditions. We then applied eight years of forcing data from a Colorado subalpine meteorological tower to analyze the impact of precipitation magnitude and timing on snowpack dynamics. The magnitude of modeled subcanopy snow accumulation depended on the length of time snow spent in the canopy, where it could sublimate. Simulated grey phase conditions resulted in 5% - 15% more peak snow water equivalent than living conditions. Modeled snowpack depletion in grey phase conditions, relative to living conditions, varied with the magnitude and timing of water year precipitation. Impacted canopy processes (*i.e.*, reduced snow
interception and sublimation, increased solar transmission) were more important during dry water years. Additionally, the influence of these processes on snow accumulation and melt decreased during years with later occurrence of snowfall.

4.2 INTRODUCTION

The mountain pine beetle (Dendroctonus ponderosae; MPB) is currently affecting more than 100,000 km² of pine forest in western North America (Allen et al., 2010). By four years post-infestation, pine canopies are often completely denuded of needles and small twigs in what is termed the “grey phase” of tree mortality (Klutsch et al., 2009; Wulder et al., 2006). Grey phase pine stands are distinctly different than burned or clear-cut stands. Unlike these other disturbed pine forests, grey phase pines experience significant canopy reduction while retaining a considerable amount of woody canopy material (Pugh and Gordon, 2012).

It is crucial to quantify the wintertime hydrologic effects of the changes in forest characteristics resulting from progression to the grey phase of tree death. Grey phase forests cover a large area and have been shown to affect snow accumulation and melt processes (Boon, 2009, 2012; Pugh and Small, 2011, in review). Living pine canopies attenuate incoming precipitation, sunlight, and wind, creating sheltered subcanopy conditions. As a result, living pine forests accumulate less snow than clearings, but often maintain snowpacks later into the melt season (see Varhola et al., 2010 for a review). Grey phase forests intercept less snow, so
sublimation from the canopy is reduced (Pugh and Small, in review). In addition, the grey phase forests transmit more solar radiation through the canopy to the ground (Pugh and Gordon, 2012) than comparable living forests. Thus, these forests are midway on the continuum between living forests and clearings in terms of important snow hydrologic processes.

MPB field studies often compare hydrology in dissimilar living and dead pine stands (e.g., different stem densities, tree heights, basal areas) and during different weather conditions (e.g., Boon, 2012; Pugh and Small, 2011). As a result, field-based observations describe a complex hydrologic response following tree death. Initial studies report augmented subcanopy snow accumulation under grey phase lodgepole pine (Pinus contorta) stands ranging from 3% to 74% (Boon, 2007, 2011; Pugh and Small, 2011, in review; Table 4.1). Pugh and Small (2011) hypothesized that the effects of this additional subcanopy snow accumulation on snowmelt timing will vary with interannual differences in snowfall magnitude. Because larger quantities of ice require more energy to melt, additional subcanopy snow accumulation under dead trees has the potential to cause snowpacks to persist later into the melt season (Boon, 2007). Conversely, in years with little snowfall, these snowpacks may melt more rapidly due to increases in melt energy associated with greater canopy solar transmissivity (Boon, 2009; Pugh and Small, 2011; Mikkelson et al., 2011; Pugh and Gordon, 2012).

We use a land surface model to isolate the effects of tree death on radiation and canopy interception, and to quantify the resulting control on timing of
<table>
<thead>
<tr>
<th>Reference</th>
<th>Study Location</th>
<th>Increase in Grey Phase Peak SWE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boon, 2007</td>
<td>British Columbia, CA</td>
<td>74%</td>
</tr>
<tr>
<td>Pugh &amp; Small, 2011</td>
<td>Colorado, USA</td>
<td>11% – 21%</td>
</tr>
<tr>
<td>Boon, 2012</td>
<td>British Columbia, CA</td>
<td>3% – 19%</td>
</tr>
<tr>
<td>Pugh &amp; Small, in review</td>
<td>Colorado, USA</td>
<td>20%</td>
</tr>
</tbody>
</table>

Table 4.1. Values of additional peak SWE under grey phase lodgepole pine stands relative to comparable living stands from previous field studies.

snowmelt. This approach has two advantages: (1) ambiguities inherent in field studies are removed (e.g., comparing forest stands with different characteristics); and (2) individual water and energy fluxes can be isolated and studied. Previous modeling attempts using spatially-distributed hydrologic models (Bewley et al., 2010; Pomeroy et al., 2012) investigated the impacts of pine beetle infestation on specific watersheds that included non-forested areas. Bewley et al. (2010) simulated two years of grey phase pine beetle infestation in the DHSVM model by altering 24 model parameters, including plant area index (PAI), maximum snow interception capacity, minimum melt needed for canopy mass release, and canopy albedo. Pomeroy et al. (2012) used the CRHM model to simulate four water years of pine beetle infestation by reducing canopy leaf area index, canopy snow interception load capacity, and suppressing plant transpiration. For all modeled water years, their results indicate increased precipitation and energy inputs to grey phase forests lead to augmented snowpacks and earlier melt.

The objective of this study is to use a 1D land surface model to (1) investigate the canopy mechanisms responsible for changes in snow accumulation and melt energy, and (2) assess the impact of interannual differences in the magnitude and
timing of water year precipitation on these mechanisms. In the following sections, we describe the model and methods of parameterization using our current understanding of hydrology developed from observations of snow accumulation, snowmelt, and micrometeorology. The model is then applied with various dead forest conditions to show the sensitivity of stand-scale hydrology to disturbances in forest cover relating to pine beetle infestation. The response of snow accumulation, snowmelt volume, and snowmelt timing are considered in detail.

4.3 METHODS

We used the Canadian Land Surface Scheme 3.5 (CLASS) process-based land surface model (Verseghy, 1991; Verseghy et al., 1993) to investigate how grey phase forest characteristics affect snow accumulation and melt. Since the changes in snow dynamics we are investigating result from canopy reduction, we chose to use a model that represents complex canopy snow interception, snow unloading, and radiation transfer processes (Bartlett et al., 2006). CLASS incorporates an advanced canopy interception and unloading scheme that varies the magnitude of intercepted snow with tree species, precipitation amount, liquid and solid precipitation states, existing snow in the canopy, and sublimating conditions (Schmidt and Gluns, 1991; Hedstrom and Pomeroy, 1998; Pomeroy et al., 1998; Storck et al., 2002). Additionally, the model accounts for the influences of canopy density on atmosphere-subcanopy radiative transmissivity and intercepted snow on canopy albedo (Hardy et al., 2004; Ni and Woodcock, 2000; Stähli et al., 2009).
4.3.1 FORCING DATA

The meteorological forcing data used to drive the CLASS model were measured at the Niwot Ridge Ameriflux Site. This tower is located approximately 25 km west of Boulder, Colorado and 8 km east of the continental divide (40° 1’ 58” N; 105° 32’ 47” W), at 3050 m elevation above sea level. The surrounding forest is dominated by subalpine fir (Abies lasiocarpa), Engelmann spruce (Picea engelmannii), and lodgepole pine (Pinus contorta). The average canopy height is 11.4 m and the average growing season leaf area index is 4.2 m² m⁻² (Turnipseed et al., 2002). Soils are sandy and derived from granitic moraine with a distinct, thin (6 - 10 cm) organic horizon (Scott-Denton et al., 2006). Snowfall accounts for 80% of the annual water input in the area and yields moderate snowpacks (Caine, 1995). Site characteristics are described in detail by Turnipseed et al. (2002).

Complete meteorological records were available for eight (2000, 2001, 2003, 2007, 2008, 2009, 2010, 2011) of the last twelve water years (2000 to 2011). These eight years of data were used to supply different observed subalpine weather forcing to CLASS, allowing for an analysis of how the shape and magnitude of precipitation and radiation records affect snow accumulation and melt. In Pugh and Small (2011, in review), field data were collected from sites that were slightly lower in elevation but experienced similar snow accumulation. Those sites were almost entirely lodgepole pine and consisted of taller trees than those surrounding the Niwot Ridge site. The Niwot ridge site was selected because it was the site most similar to those
in Pugh and Small that had the complete forcing dataset. The effects of these differences on our study are likely negligible because we used above-canopy forcing measurements. Possible differences resulting from topography are addressed in the discussion.

We use four metrics to describe precipitation and SWE record timing and shape. First, $P50$ describes the day of year (DoY) when 50% of water year precipitation has occurred, indicating whether a given year received the majority of precipitation during the winter or spring. Second, depletion date is the first DoY following peak SWE when all snow has melted (i.e., SWE = 0 mm). Third, melt rate is a metric for the speed at which snow is depleted and is calculated as

$$Melt\ Rate = \frac{Peak\ SWE}{Depletion\ Date - Peak\ SWE\ Date},$$

where $Peak\ SWE\ Date$ is the DoY when peak SWE occurred. Fourth, April 1 precipitation anomaly is the percent difference of April 1 cumulative precipitation for a given water year from the 2000-2011 average as recorded at the SNOTEL site (described in the next subsection).

4.3.2 SNOTEL SITE

SNOTEL site CO663 (NRCS National Water and Climate Center, 2012) provided records of historical water year SWE accumulation and melt timing, enabling comparisons with modeled records. SNOTEL site CO663 is roughly 0.5 km from the meteorological tower in a 7-m-wide, flat forest clearing, with a clearing-width-to-tree-height ratio of ~0.75. The SNOTEL site is 30 m lower in elevation
than the met tower. Data from the SNOTEL site is considered to represent a forest clearing. We only compare model data for canopy-free conditions to the SNOTEL record.

*CLASS* was run for eight water years for non-vegetated conditions (*i.e.*, a clearing). Resulting modeled SWE records were compared to records from SNOTEL site CO663 (Figure 4.1). Modeled peak SWE was on average 3(±9)% higher than SNOTEL observations and modeled snowpack depletion occurred an average of 17(±5) days later, suggesting melt rates on average 2.6 mm d⁻¹ slower in modeled clearings relative to SNOTEL observations.

Good model performance was demonstrated in simulating snow accumulation under clearing conditions, but modeled snowpacks persisted roughly two weeks longer than SNOTEL records. Some of this error during snowmelt may have arisen from the fact that the SNOTEL site, while not directly under canopy, was surrounded by trees. These trees could have led to additional longwave reemission (*Rouse*, 1984), warmer near-snowpack temperatures (*Pomeroy et al.*, 2009), and reduced snowpack albedo from tree litter (*Melloh et al.*, 2001). Additionally, the SNOTEL site was roughly 0.5 km away from the met tower. Such a distance in mountainous terrain could have led to different springtime melt conditions at the two sites. These differences in vegetation and location may have caused modeled
Figure 4.1. Modeled SWE and snowpack density records for water year 2011 graphed along with SNOTEL observations. Only one of modeled dead conditions ($U = 0.5$ days) records is displayed here.

clearing snowpacks to deplete later. Alternatively, this bias toward slower modeled melt rates could be inherent to CLASS (i.e., snowpack albedo settings), in which case it likely also impacted modeled forest conditions.
4.3.3 CANOPY MODEL PARAMETERIZATION

Subcanopy snow accumulation in CLASS 3.5 is sensitive to multiple canopy process algorithms, including canopy density, interception capacity, and unloading (Bartlett et al., 2006). The influence of canopy snow interception, sublimation, and unloading parameters on subcanopy snowpacks was analyzed, with plant area index (PAI), canopy snow unloading timescale (U), and canopy albedo (\(a_c\)) impacting snow accumulation the most (Figure 4.2). Changes in PAI had the largest effect, on both SWE and depletion date. A 25% increase or decrease in living condition PAI, U, and \(a_c\) parameter values resulted in 35 mm, 14 mm, and 6 mm changes to peak SWE, respectively. These 25% changes to parameters also resulted in 4.5 day, 0.5 day, and 0.5 day changes to depletion date, respectively. Similar changes to the species-specific canopy maximum snow loading coefficient (\(S_p\)) and moisture transfer coefficient (TC) resulted in negligible changes to peak SWE.

We selected values for PAI based on photo-derived estimates of canopy cover. Pugh and Gordon (2012) took hemispherical photographs in 39 lodgepole pine stands across northern Colorado. They observed significantly lower plant area index (PAI) in grey phase stands than in living stands. PAI is defined as the product of a foliage clumping factor (Nilson, 1971) and the leaf area index (Black et al., 1991). When derived from hemispherical photography, values of PAI reflect total plant area (i.e., include estimates of canopy woody material). Pugh and Gordon observed that PAI covaried with stand basal area in both living and dead stands, with larger stem
Figure 4.2. Living and dead \((U = 0.5d)\) condition peak SWE and depletion date values resulting from a ±25% change in relevant living condition model parameters: plant area index \((PAI)\), canopy snow unloading timescale \((U)\), canopy albedo \((\alpha_c)\), canopy maximum intercepted snow load coefficient \((S_p)\), and moisture transfer coefficient \((TC)\). Changes equal to 25% of the living conditions parameters were also applied to dead conditions. The effects of these adjusted parameters were modeled using water year 2009, an average precipitation year.

densities and/or trunk diameters often indicating more complete forest canopy. As a result, they divided study stands into low basal area \((15 – 35 \text{ m}^2 \text{ ha}^{-1})\) and high basal area \((35 – 65 \text{ m}^2 \text{ ha}^{-1})\) classes. Additionally, they used photo-derived \(PAI\) values to model canopy solar transmission using a modified Beer-Lambert model for light flux (Hellström, 2000). Photos were taken early in the month of August. Here, we use their modeled estimates of canopy solar transmission to tune the \(PAI\) parameter in the \(CLASS\) model (Figure 4.3). By varying the \(CLASS\) \(PAI\) parameter and observing the effect that this change had on 1 Aug canopy solar transmission, we selected \(PAI\) values that represent the widest range of transmissivity values.
Canopy transmission values from Pugh and Gordon (2012) are placed on the line created by connecting the modeled data points, indicating appropriate PAI values for each class: high basal area living stands (LH), high basal area grey phase stands (GH), low basal area living stands (LL), and low basal area grey phase stands (GL). PAI values of 3 and 2 were selected to represent living and dead conditions in this modeling study because those are the most extreme values within one standard deviation (error bars) of mean transmissivity for both high and low basal area classes.

within one standard deviation of Pugh and Gordon’s means for both high and low basal area classes. Values of 3 and 2 were selected to represent living and dead conditions, respectively.

We also incorporate a modification to the canopy snow unloading timescale parameter (U). MacKay and Bartlett (2006) noted that the standard CLASS U value of 10 days may result in an underestimation of subcanopy snow accumulation because of inflated canopy snow sublimation. They suggest more realistic values fall in the range of 1 to 2 days. Here, a value of 1.5 days was selected for living U.
These values are consistent with our field observations from a recent snow interception study (*Pugh and Small*, in review a). In almost all cases during that study, intercepted snow was gone from trees within 2 days.

All other *CLASS* parameters (*e.g.*, canopy albedo, maximum interception branch-snow-loading coefficient, soil moisture suction) chosen to represent a living forest were selected based on model documentation for conifer forests (*Verseghy et al.*, 2011; Table 4.2). With these parameters applied, *CLASS* reasonably modeled living stand snow accumulation and melt (described further in the Results section).

### 4.3.4 DEAD CONDITIONS PARAMETER SELECTION

The influences that the *PAI*, *U*, and *a_c* parameters have on modeled canopy snow processes were further analyzed and used to guide the selection of *CLASS* settings for four dead conditions. Notable observations from these analyses are that evapotranspiration was more sensitive to changes in *U* during dry water years, as opposed to wet water years, and peak SWE was more sensitive to changes in *PAI* during dry years (Figure 4.4). Our two primary dead conditions consist of suites of changes mimicking moderate and extreme modifications to canopy properties. In both cases *PAI* was reduced from 3 to 2. Additionally, both conditions have an increased value of *a_c*. The albedo of the canopy was increased from 0.19 to 0.23, mirroring the 0.04 increase in grey phase forest albedo observed by *O'Halloran et al.* (2012). The increase in *a_c* observed by *O'Halloran et al.* in dead stands likely
Table 4.2. CLASS plant area index (PAI), maximum time for canopy snow unloading (U), and canopy albedo (αc) parameter values used for the six modeled conditions. The clearing class was modeled without a vegetation canopy layer. For the Dead (Altered Radiation Only) class, αc was increased and PAI was decreased for transmissivity calculations only. For the Dead (Altered Interception Only) class, U was decreased and PAI was decreased for interception calculations only.

<table>
<thead>
<tr>
<th>Class</th>
<th>PAI – Radiation (m m⁻²)</th>
<th>PAI – Interception (m m⁻²)</th>
<th>U (days)</th>
<th>αc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living</td>
<td>3.0</td>
<td>3.0</td>
<td>1.5</td>
<td>0.19</td>
</tr>
<tr>
<td>Dead (0.75d)</td>
<td>2.0</td>
<td>2.0</td>
<td>0.75</td>
<td>0.23</td>
</tr>
<tr>
<td>Dead (0.5d)</td>
<td>2.0</td>
<td>2.0</td>
<td>0.5</td>
<td>0.23</td>
</tr>
<tr>
<td>Dead (Altered Radiation Only)</td>
<td>2.0</td>
<td>3.0</td>
<td>1.5</td>
<td>0.23</td>
</tr>
<tr>
<td>Dead (Altered Interception Only)</td>
<td>3.0</td>
<td>2.0</td>
<td>0.5</td>
<td>0.19</td>
</tr>
<tr>
<td>Clearing</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Figure 4.4. Sensitivity of April evapotranspiration and peak SWE to the maximum canopy unloading timescale (U) and plant area index (PAI) during dry, normal, and wet water years. Living and dead conditions parameter selections are displayed as black and grey lines, respectively.
resulted from both a visibly lighter canopy following needle loss and a thinner canopy which allowed for more subcanopy snow reflection. Finally, we observed more subcanopy snow accumulation under grey phase canopies relative to reductions to the $U$ parameter, shortening the time that modeled canopy snow is exposed to canopy conditions suitable for sublimation. Pugh and Small (in review a) hypothesized that additional dead stand snow accumulation is partly due to more rapid canopy snow unloading from changes in post-mortality branch orientation, canopy area, and canopy wind speeds. Here we reduce the $U$ parameter from 1.5 days in living conditions to 0.75 days and 0.5 days in two dead conditions, yielding moderate and extreme scenarios with which to test this hypothesis.

We isolated the effects of changes in radiation and snow interception by completing simulations with two additional sets of parameters. To isolate impacts on the energy balance, PAI was reduced from 3 to 2 for all canopy radiation transmission and albedo calculations, but left at 3 for canopy snow interception calculations. Canopy albedo was also increased from 0.19 to 0.23. Similarly, to isolate the impacts of reduced canopy on the water balance, PAI was reduced from 3 to 2 for all canopy snow interception calculations, but left at 3 for canopy radiation transmission and albedo calculations. Additionally, $U$ was reduced from 1.5 days to 0.5 days, further diminishing the ability of the canopy to retain snow. Final parameter settings for the six living/dead/clearing classes are summarized in Table 4.2.
4.4 RESULTS

4.4.1 SNOW ACCUMULATION AND MELT

Findings in this subsection are the result of applying eight years of forcing data to CLASS. As such, they represent average values from a range of meteorological conditions. On average, modeled peak SWE was 70(±19)% greater under clearing conditions than living forest conditions (Figure 4.1; Table 4.3). This additional SWE under clearing conditions generated an average of 34(±22)% more water from snowmelt. However, canopy solar shading in living conditions resulted in 3.5(±1.5) mm d⁻¹ slower snowmelt rates, causing living condition snowpacks to persist an average of 2.8(±3.4) days longer than clearing snowpacks.

The three modeled dead conditions with altered interception parameters accumulated more peak SWE than living conditions. Greater additional peak SWE occurred with smaller values of the \( U \) parameter (Table 4.3). In the dead conditions with a \( U \) value of 0.75 days, 5(±4)% more subcanopy snow had accumulated by peak SWE than in living conditions. This additional peak SWE was increased to 10(±4)% when the \( U \) parameter was reduced to 0.5 days. The dead conditions with a \( U \) value of 0.5 days but no changes to canopy radiation transmission led to the most additional subcanopy accumulation with 13(±6)% more peak SWE. Conversely, the dead forest conditions that did not incorporate changes to interception parameters (i.e., applying dead conditions to radiation parameters only) resulted in 6(±5)% less peak SWE than living conditions, highlighting the interplay between peak SWE and springtime melt energy.
Table 4.3. Differences observed between modeled living and dead/clearing conditions, including additional SWE, additional water generated by snowmelt, additional melt rate, and change in depletion date. Values are reported as a mean ± one standard deviation.

<table>
<thead>
<tr>
<th>Class</th>
<th>Additional Peak SWE (%)</th>
<th>Additional Water Generated (%)</th>
<th>Additional Melt Rate (mm day⁻¹)</th>
<th>Change in depletion date (days earlier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead (0.75d)</td>
<td>4 ± 5</td>
<td>24 ± 13</td>
<td>0.3 ± 0.2</td>
<td>3.1 ± 2.6</td>
</tr>
<tr>
<td>Dead (0.5d)</td>
<td>10 ± 4</td>
<td>34 ± 18</td>
<td>0.3 ± 0.1</td>
<td>0.0 ± 0.5</td>
</tr>
<tr>
<td>Dead (Altered Radiation Only)</td>
<td>-6 ± 5</td>
<td>-14 ± 5</td>
<td>-0.3 ± 1.0</td>
<td>4.3 ± 2.8</td>
</tr>
<tr>
<td>Dead (Altered Interception Only)</td>
<td>13 ± 6</td>
<td>33 ± 17</td>
<td>0.3 ± 0.3</td>
<td>-2.3 ± 2.1</td>
</tr>
<tr>
<td>Clearing</td>
<td>70 ± 19</td>
<td>34 ± 22</td>
<td>3.5 ± 1.5</td>
<td>2.8 ± 3.4</td>
</tr>
</tbody>
</table>

Snowpacks under dead conditions lasted both longer and shorter than living conditions, depending on the radiation and interception parameters applied. Snowpacks in the modeled dead conditions where radiation parameters were not changed from living settings persisted the longest, with depletion dates averaging 2.3(±2.1) days later than living conditions. On the contrary, snowpacks in the modeled dead conditions where interception parameters were not changed from living settings depleted 4.3(±2.8) days earlier. Depletion dates varied with values of $U$ for the remaining two dead conditions, with shorter unloading times yielding later snowpack depletion (Table 4.3).

4.4.2 RADIATION AND ENERGY BALANCE

Figure 4.5 displays the average of energy-balance components modeled in clearing, living, and dead conditions during the April ablation period of all eight modeled water years. The results indicate that net shortwave ($K^*$) at the snowpack
Figure 4.5. The average of energy-balance components modeled in clearing, living, and dead conditions during the April ablation period of all eight modeled water years. Both canopy (solid lines) and subcanopy (dashed lines) fluxes are displayed.
Figure 4.6. Percent additional shortwave radiation modeled under dead conditions relative to living conditions graphed versus time. Both subcanopy shortwave ($K_{subcanopy}$) and net shortwave ($K_{net}$) are displayed. Error bars indicate one standard deviation from the eight-model-year mean.

<table>
<thead>
<tr>
<th>Class</th>
<th>Subcanopy Shortwave (%)</th>
<th>Net Shortwave (%)</th>
<th>Canopy Sublimation (%)</th>
<th>Snowpack Sublimation (%)</th>
<th>Total Sublimation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead (0.75d)</td>
<td>+42 ± 1</td>
<td>-2.7 ± 0.1</td>
<td>-35 ± 3</td>
<td>-13 ± 7</td>
<td>-31 ± 3</td>
</tr>
<tr>
<td>Dead (0.5d)</td>
<td>+42 ± 1</td>
<td>-2.5 ± 0.2</td>
<td>-51 ± 4</td>
<td>-14 ± 7</td>
<td>-45 ± 3</td>
</tr>
<tr>
<td>Dead (Altered Radiation Only)</td>
<td>+45 ± 0</td>
<td>-2.5 ± 0.0</td>
<td>-6 ± 14</td>
<td>-2 ± 21</td>
<td>-6 ± 13</td>
</tr>
<tr>
<td>Dead (Altered Interception Only)</td>
<td>+3 ± 6</td>
<td>-0.1 ± 0.0</td>
<td>-50 ± 10</td>
<td>-12 ± 21</td>
<td>-44 ± 10</td>
</tr>
<tr>
<td>Clearing</td>
<td>n/a</td>
<td>+12 ± 6</td>
<td>n/a</td>
<td>+133 ± 38</td>
<td>-61 ± 7</td>
</tr>
</tbody>
</table>

Table 4.4. Percent differences in modeled shortwave radiation and snow sublimation in dead/clearing classes relative to living conditions. Values are reported as a mean ± one standard deviation.
was inversely related to class \textit{PAI}, with clearing conditions receiving the most $K^*$ and dead conditions on average receiving 42% more subcanopy shortwave than living conditions (Figure 4.6; Table 4.4). $K^*$ represents the dominant input to snowmelt energy in all conditions. $K^*$ at the canopy was 2.5% lower in dead conditions than living conditions, suggesting that reductions from greater canopy albedo mitigated potential increases resulting from greater solar transmissivity (Figure 4.6). Applying dead conditions to only interception parameters did not cause significant changes to either net shortwave or subcanopy shortwave.

Daily average net longwave ($L^*$) at the snowpack increased with \textit{PAI}, changing from negative values in clearing conditions to positive in the living and dead forest conditions. While positive in value, $L^*$ at the snowpack in dead conditions was less variable than living condition $L^*$ and resulted in a 96% reduction in average $L^*$ compared to living conditions. Average daily sensible heat fluxes ($Q_H$) did not vary appreciably between living and dead conditions. However, $Q_H$ was more variable in dead conditions, with 33% greater peak $Q_H$ in dead conditions.

Snowpack sublimation increased with decreasing \textit{PAI} such that sublimative losses from the snowpack represent all sublimation from clearing conditions and represent a greater portion of total sublimation losses in modeled dead conditions than in living conditions (Figure 4.7). Peak daily latent heat fluxes ($Q_E$) from the snowpack were 11% greater in dead conditions than living conditions. However,
average daily $Q_E$ from the snowpack in dead conditions was 2% lower than in living conditions.

Latent heat flux was greater in modeled living canopies than dead canopies, resulting in 54% and 104% more canopy snow sublimation in living conditions than in dead conditions with $U$ values of 0.75 days and 0.5 days, respectively (Figure 4.7). Results from the radiation-only dead conditions suggest a small portion (~15%) of the reduction in dead stand canopy sublimation is due to changes in canopy energetics (Table 4.4). Total snow sublimation (i.e., from both snowpack and canopy sources) was the greatest in living forest conditions and decreased with smaller $PAI$ and $U$ values. On average, total snow sublimation in living conditions was 44%, 82%, and 156% greater than in dead ($U=0.75d$), dead ($U=0.5d$), and clearing conditions, respectively.

### 4.4.3 INTERANNUAL VARIABILITY

Changes to peak SWE and snowpack depletion date under dead conditions varied with the magnitude and timing of water year precipitation. On a percentage
Figure 4.8. Percent additional peak SWE in four dead conditions graphed against April 1 precipitation anomaly. Additional SWE is significantly correlated with precipitation anomaly for only the dead conditions with the shorter canopy snow unloading time (0.5 days): (dead (altered interception only): $r^2=0.78$, $p<0.01$; dead(0.5d): $r^2=0.42$, $p=0.05$; dead (0.75d): $r^2=0.21$, $p=0.26$; dead (altered radiation only): $r^2=0.37$, $p=0.18$).

basis, modeled dead conditions led to the accumulation of more snow relative to living conditions during drier water years, highlighting the importance of canopy effects during low snow conditions (Figure 4.8). Percentage additional peak SWE in dead conditions is negatively correlated with the April 1 Precipitation Anomaly for the two dead conditions with the shorter $U$ value of 0.5 days (dead (altered interception only): $r^2=0.78$, $p<0.01$; dead(0.5d): $r^2=0.42$, $p=0.05$). Additionally, depletion dates in all four dead conditions were correlated with the $P50$ water year statistic (Figure 4.9), emphasizing the connection between the timing of snowfall and solar zenith angles (dead (altered interception only): $r^2=0.77$, $p<0.01$; dead (0.5d): $r^2=0.73$, $p<0.01$; dead (0.75d): $r^2=0.73$, $p<0.01$; dead (altered radiation only):
\( r^2 = 0.74, p < 0.01 \). The later in the season that snowfall occurred, the less impact both interception and transmission processes had on snowmelt timing.

4.5 DISCUSSION

The findings described in the results sections suggest canopy reduction associated with pine beetle infestation will lead to additional snow accumulation in the range of 5% - 15% and increased subcanopy snowmelt energy. Because of diminished canopy interception and more rapid snow unloading, more snow accumulated in the subcanopy of modeled dead conditions. Modeled estimates of additional snow accumulation are similar to observations from recent MPB-snow field studies (Table 4.1). This additional subcanopy snow in dead conditions alters the subcanopy energy balance beyond the effects of increases in canopy radiation transmissivity. While greater canopy transmissivity may lead to increased daily values of \( Q_H \) and \( Q_E \), the effect of these increases is likely mitigated by the extra cold content of augmented dead condition snowpacks. This may explain the greater variability of the \( Q_H \) and \( Q_E \) terms in modeled dead conditions.

The modeled melt timing of these augmented dead condition snowpacks depends on a number of factors including the magnitude and timing of water year precipitation. Other factors, such as the availability of dry water year forcing data and assumptions about site topography, could have also influenced modeling results. Forcing data from very low snow years (e.g., 2002, 2004) were not available at this study site. Because maximum intercepted snow loads are more readily met
Figure 4.9. Change in depletion date under dead conditions graphed against $P50$. Change in depletion date is significantly correlated with $P50$ for all dead unloading conditions (dead (altered interception only): $r^2=0.77$, $p<0.01$; dead (0.5d): $r^2=0.73$, $p<0.01$; dead (0.75d): $r^2=0.73$, $p<0.01$; dead (altered radiation only): $r^2=0.74$, $p<0.01$).

and the canopy mechanically unloads snow more often during wet water years, these dry water years may have yielded more extreme results. Moreover, the modeling experiment performed here assumes flat terrain and complete forest cover, two site characteristics that are rare in the southern Rocky Mountains. Real world hydrologic responses would likely depend on site slope, aspect, forest cover, and the extent of mortality (Ellis and Pomeroy, 2007; Pomeroy et al., 2012; Pugh and Gordon, 2012). Specifically, the slope and aspect of a forested site is an important predictor of the subcanopy energy balance; in the northern hemisphere, south-facing tree stands receive more sunlight than north-facing stands (Ellis et al., 2011). Differences in melt timing observed between impacted stands and living
stands in Colorado \textit{(e.g., earlier relative depletion in Pugh and Small, 2011)} versus British Columbia \textit{(e.g., later relative depletion in Boon, 2009)} may be the result of latitude, with the solar zenith angle relative to the angle of snow playing an important role in controlling the energy available for snowmelt. Additionally, high elevation watersheds are often not completely forested, suggesting the stand-scale snowmelt volume estimates from this study (>24% more snowmelt in dead pine stands than living stands) would likely be overestimates at the watershed-scale. Better estimates could potentially be made at larger scales by running \textit{CLASS} in a spatially-distributed mode while employing the 0.75d or 0.5d dead stand parameter selections utilized in this study.

This modeling exercise can be instructive on the selection of appropriate dead forest model parameters. Previous modeling efforts have thought it sufficient to alter only the \textit{PAI} parameter to simulate canopy reduction associated with pine beetle infestation \textit{(e.g., Mikkelson et al., 2011)}. However, because pine beetle infestation only moderately reduces stand-scale \textit{PAI}, varying \textit{PAI} alone is not an adequate method of parameterizing advanced land surface models for the prediction of subcanopy snow accumulation and melt under dead pine forests. Interception parameters (such as $U$ or $S_p$) should be changed in addition to \textit{PAI} in order to simulate the diminished interception efficiency of dead canopies \textit{(e.g., Pomeroy et al., 2012)}. 
4.6 CONCLUSIONS

We made select parameter adjustments to the physically-based CLASS 3.5 model to investigate the effects of moderate canopy reduction on snow accumulation and melt processes. We then applied eight years of forcing data to analyze the impact of precipitation magnitude and timing on snowpack dynamics. Reductions in canopy area and snow unloading timescales led to additional snow accumulation in the range of 5% - 15%, changes smaller than those resulting from interannual variation (i.e., wet or dry water years). Results suggest both subcanopy snow accumulation and melt timing in dead conditions are highly sensitive to the length of time snow remains in the tree canopy, where snow is more likely to sublimate. Because small changes in canopy snow unloading timescales lead to large changes in depletion date, the ability to predict snowmelt timing may depend strongly on the availability of canopy snow unloading field measurements. However, the importance of altered canopy processes in dead stands (i.e., reduced snow interception and sublimation, increased solar transmission) decreases with greater water year precipitation, as canopy maximum intercepted loads are more readily met and more subcanopy snow exists, requiring additional energy to melt. Additionally, the later snow falls during a given water year, the less important canopy processes become and the more important sun angle becomes. Thus, there is potential for additional water yield given particular site topography (i.e., shaded slopes) and water year precipitation attributes (i.e., low magnitude, early-season precipitation). Future efforts that expand this stand-scale modeling approach to the
watershed-scale may be able to quantify the impact of tree death on snowmelt-derived streamflow.
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