

THE IMPACTS MOUNTAIN PINE BEETLE ON FORESTED SNOWPACKS:
ACCUMULATION AND ABLATION

by

Christopher Michael Welch

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

April 2013

©COPYRIGHT

by

Christopher M. Welch

2013

All Rights Reserved

APPROVAL

of a thesis submitted by

Christopher Michael Welch

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to The Graduate School.

Dr. Paul Stoy

Approved for the Department of Land Resources and Environmental Sciences

Dr. Tracy Sterling

Approved for The Graduate School

Dr. Ron Larsen

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Christopher M. Welch

April 2013

ACKNOWLEDGEMENTS

This thesis would not have been possible were it not for the support, advice, and guidance of my committee chair, Dr. Paul Stoy. He has always shown a steadfast commitment toward the advancement of my knowledge and has routinely provided the inspiration and motivation necessary to advance my understanding of the world through research. Through out the time that we have worked together, Paul has made my educational experience positive, enlightening, and memorable. I would also like to extend my gratitude to my committee members Dr. Lucy Marshall, and Dr. Brian McGlynn. Their advice, classes, and comments helped immensely with the direction and focus of my work. Brian's support in the field also deserves special thanks, and his legacy of work in the Tenderfoot Creek Experimental Forest is what provided the opportunity to build off an incredibly well studied watershed. I would also like to thank the members of the Stoy Lab, at Montana State University, Aaron Rains and Aiden Johnson for their motivation, intellectual stimulation, and friendship. These two gentlemen were incredible assets both in and out of the field, and their alacrity to help was true testament of their generous character. Additionally, I extend my gratitude to Paddy Stoy, Fabian Nippgen, and Kelsey Jencso for their support and advice both in and out of the field, as well as their humor. Special thanks go out to the Montana Water Center for their dedication to the advancement of hydrological knowledge and for providing financial support. Finally, I would like to acknowledge and thank my family and Sarah Howell, for their love, encouragement, and friendship.

TABLE OF CONTENTS

1. INTRODUCTION	1
Scientific Background	1
The Mountain Pine Beetle	1
Impacts of the Mountain Pine Beetle on Snow	2
TCEF General Description	7
SNOTEL General Description	8
Study Objectives	9
References Cited	11
2. THE IMPACTS OF FOREST MANAGEMENT AND THE MOUNTAIN PINE BEETLE ON SNOW ACCUMULATION AND ABLATION	17
Introduction	18
Objectives	20
Methods	22
Study Location and Characteristics	22
TCEF	22
Stringer Forest Site	23
Spring Park Clearcut Site	25
Quartzite Ridge Forest Comparison Site	26
SNOTEL	27
Measurements	28
Stand Comparisons	28
Snow Surface Temperature	28
Snow Pits	28
Snow Tubes/Snow Course Measurements	29
Leaf Litter Baskets	30
Modeling	30
Snow Energy Balance	30
Sensible and Latent Heat Flux	30
Filters	32
Snow Depth	32
Temperature	33
Shortwave Radiation	33
Longwave Radiation	34
Albedo	34
Soil Heat Flux	34
Sensible and Latent Heat	35
Uncertainty Analysis	35

TABLE OF CONTENTS – CONTINUED

Results	35
Stand Characteristics.....	35
Microclimate.....	36
Snow Water Equivalent	36
Snow Depth.....	37
Snow Temperature	38
Patterns in Incident Shortwave Radiation.....	38
Albedo.....	40
Longwave Radiation and Snow Surface Temperature.....	40
Net Radiation	41
Latent Heat Flux	42
Sensible Heat Flux	42
Ground Heat Flux	43
Total Energy.....	43
Discussion	47
Interannual Variability	45
Clearcut.....	45
Subcanopy.....	47
Infested.....	48
Site Variability.....	49
Shortwave Radiation.....	49
Scenario Analysis: Changing incoming SW	50
Scenario Analysis for Albedo	50
Longwave Radiation	51
Scenario Analysis: Changing LW_{net}	52
Sensible Heat and Latent Heat.....	52
Model Assessment for H and λ	53
Model Sensitivity	54
References Cited.....	80
3. CONCLUSIONS/SUMMARY	85
REFERENCES CITED.....	89

LIST OF TABLES

Table	Page
1. Characteristics of the forest stands at the Tenderfoot Creek Experimental Forest (TCEF) study site	55
2. Sensor Locations	55

LIST OF FIGURES

Figure	Page
1: Components that impart a physical influence on snow energy dynamics. A canopy reduced by MPB is likely to experience increased transmission of SW_{in} , while the more open sky is likely to increase LW_{out} . Additionally, through fall is likely to increase due to the lower stem density for interception. Characteristics of the forest stands at the Tenderfoot Creek Experimental Forest (TCEF) study site.....	10 & 56
2: Elevation Map of TCEF with site locations.....	57
3: Average daily temperatures for Onion Park, Stringer Creek, subcanopy, and infested sites during the melt periods of 2011 (A) and 2012 (B).	58
4: Precipitation (mm) at Onion Park Snotel for water year of 2011-2012.....	59
5: Snow Water Equivalent from January 1 through June 27 for 2011 and 2012 from 1 and 3 hour readings as available for the Onion Park (A) and Stringer Creek (B) SNOTEL sites.	59
6: Snow depth as recorded at Stringer Creek, Onion Park, subcanopy, infested, healthy, and clearcut sites in (A) 2011 and (B) 2012.	60
7: Measured snow temperature at different heights in the snowpack during the melt period of 2011 (noon time values) and 2012 (daily averages) at the infested site, emphasizing the point around day of year 126 (2011) and 80 (2012) at which the snowpack becomes isothermal.	61
8: Interpolated snow temperature at the infested site, for the winter of 2011-2012, using observations of air temperature and a snow temperature ladder.	62
9: Cumulative net (SW_{net}), incident (SW_{in}) and outgoing (SW_{out}) shortwave radiation flux during melt peirods of 2011 and 2012 at the clearcut, subcanopy, infested and healthy study sites.	63
10: Noontime albedo for the 2011 (A) and 2012 (B) melt season at the study stands in the TCEF experimental forest, using a 10 reading running average for display.	64

LIST OF FIGURES – CONTINUED

Figure	Page
11: Cumulative net (LW_{net}), incoming (LW_{in}) and outgoing (LW_{out}) longwave radiation for melt periods of 2011 and 2012 for clearcut, subcanopy, infested, and healthy sites.	65
12: Cumulative available radiation at the snow pack including SW_{net} , SW_{in} , SW_{out} , LW_{net} , LW_{in} , and LW_{out} for the subcanopy, clearcut, and infested in 2011, with the addition of the healthy in 2012.	66
13: Modeled cumulative H , λE , and measured G flux at the clearcut, subcanopy, infested, sites in 2011, and with the addition of the healthy in 2012.	67
14: Cumulative energy to snowpacks including R_n , H , λE , and G over the period of observed declining snowpacks for the clearcut, subcanopy and infested sites in 2011, with the addition of the healthy site in 2012.	68
15: Clearcut SW_{in} under reduction scenarios for 2011 and 2012 with the subcanopy and infested site actual measurements for reference.	69
16: Effects on clearcut Q_m with approximate canopy attenuation on transmission for 2011 and 2012 with subcanopy and infested sites for reference.	70
17: LW_{net} at the clearcut under scenarios of increasing canopy cover for 2011 and 2012 with the subcanopy and infested sites for reference.	71
18: Effects on clearcut Q_m with LW_{in} increased by 10% in 2011 and 20% in 2012 to mimic that of the forested sites.	72
19: Contributions of SW_{in} of the subcanopy site under scenarios in which albedo from the clearcut, subcanopy, and healthy sites are parameterized.	73
20: SW_{in} at the infested site with the subcanopy running noontime average albedo parameterized.	74
21: Leaf litter mass collected over winter of 2011-2012	74

LIST OF FIGURES - CONTINUED

Figures	Page
22: Cumulative totals of measured λE compared to model calculated using the bulk aerodynamic theory	75
23: H measured and three models tested.....	76
24: Measured and modeled cumulative H	77
25: Scatter plot of measured and modeled H assuming neutral atmospheric stability	78
26: Scatter plot of measured and modeled H with a diabatic correction factor for unstable and stable atmospheric conditions.....	79

ABSTRACT

The future of water resources in the west is tenuous, as climatic changes have resulted in earlier spring melts that have exacerbated summer droughts. Associated with climate changes to the physical environment are changes to the biological environment that may impact snow dynamics; namely via the massive outbreaks of Mountain Pine Beetle (MPB; *Dendroctonus ponderosae*) that have devastated several million hectares of Lodgepole Pine forests in the western U.S. and Canada. If snow accumulation and melt are determined by the physical environment of the snowpack, and forest canopies define in part this physical environment, how might recent insect outbreaks alter the timing and intensity of snowmelt?

MPB often attack in large numbers, and within a few years, the canopy of an infected forest will turn from green but dying, to red, to grey. As needles fall, impacts on the snow pack include changes to wind driven transport, temperature gradients, and snow interception. Additionally, the shifting canopy alters the radiated physics of the canopy, specifically the shortwave/longwave flux density. Combined with a corresponding decrease of snow reflectance (albedo) from litter fall, the dying canopy will provide more energy available to the surface and likely drive snowpacks to melt more rapidly. Conversely, the diminished canopy cover will presumably decrease net longwave radiation of the snowpack. Canopy interception of snow is expected to decrease, and an increase in accumulation will result. I investigate the impacts of MPB disturbance on snow melt through modeling and micrometeorological measurements in intact lodgepole pine and mixed coniferous forests, a MPB-infested forest in the red stage, and a clearcut stand. Albedo at the homogenous intact stand is found to be 16 and 34% higher than the red stand during the melt periods of 2011 and 2012, but no significant difference is found between the red stand and the more heterogeneous ‘healthy’ stand. Modeled sensible heat over-predicts sensible heat by over 300% during the melt period of 2012. Results highlight the role of beetle-infested and mixed stands on altering snow albedo, and additionally suggest that model formulations for turbulent exchange between snow and atmosphere below forest canopies require improvement

CHAPTER 1

INTRODUCTION

Scientific Background

The Mountain Pine Beetle

The Mountain Pine Beetle (MPB) is a dark brown to black bark boring beetle about 6mm long that generally produces one generation per year in lodgepole pine (*Pinus contorta*) (Amman 1977). It occurs naturally in whitebark, ponderosa, lodgepole and other pine ecosystems, with evidence of outbreaks occurring over 220 years ago before intensive anthropogenic management (Roe & Amman, 1970). The most aggressive member of its genus in the western United States, it often infests a given area of forest every 20 to 40 years, depending on how rapidly trees reach a large diameter and produce thick phloem (Amman 1977). The beetle attacks *en masse* through the use of attractant pheromones to find suitable hosts (Wood, 1982). While feeding on phloem, it introduces a blue-stained fungus that is often the agent of mortality by decreasing water and nutrient transport in the sapwood (Amman, 1977). Larger diameter lodgepole pine are more susceptible to MPB; for example, Cole and Ammon (1969) found that one percent of lodgepole pine with diameter at breast height (DBH) of 4.5 inches (11.4 cm) died from infestation, compared with 87.5 percent of lodgepole pines with DBH of 16 inches (40.6 cm) or larger. Lodgepole pine are shade intolerant, and disturbance plays a large role in providing saplings room to grow and regeneration to occur (Logan, & Powell, 2001). The

MPB facilitates this process by killing over story trees and thus creating an environment suitable for Lodgepole pine recruitment (Logan, & Powell, 2011).

MPB attacks vary in size and intensity, and can be characterized as endemic and epidemic attacks (Helie, et. al, 2005). Endemic attacks result in patchy mortality throughout a stand where many large individual trees die, but others do not (Samman & Logan, 2000). If a stand is dominated by large diameter trees that are collectively unable to ‘pitch out’ attacking MPBs, an epidemic outbreak can occur. The result is upwards of 80 percent mortality over a period of just five to seven years (Samman & Logan, 2000). The most recent epidemic MPB attack is of a magnitude larger than any other previously recorded (Mitton & Ferrenberg, 2012; Raffa et al., 2008). The MPB is the primary mortality agent in forested lands in Montana, with over 36 million trees infested over 2.79 million hectares mapped as ‘infested’ from 2009 through 2011 (Denitto et al., 2011). Additionally, the peak infestation years of the most recent epidemic will continually alter canopy characteristics, as needles from trees are lost 3-5 years after death (Mitchel et al., 1998).

Impacts of the Mountain Pine Beetle on Snow

Snow deposition and ablation are a function of cover or exposure by topography and vegetation (Marks & Winstral, 2001). Snow ablation and accumulation rates are controlled in part by wind scouring, solar radiation flux, and snow interception, all which are closely tied with the canopy structure that the MPB is drastically changing (Harestad and Bunnell, 1981). Varhola et al. (2010) synthesized the results of 33 studies and found that 57% of variance of relative changes in snow accumulation was explained by

changes in forest cover and 72% of variance of relative changes in snow ablation was explained by changes in forest cover. Increased snow accumulation is linked to a decrease in canopy cover, due to the loss of snow to sublimation that was intercepted (e.g. Pomeroy, Gray, Hedstrom, & Janowicz, 2002, Varhola, Coops, Weiler, & Moore, 2010). Molotch et al. (2009), for example, reported a 29% increase in snow accumulation in open versus under-canopy sites. Assuming unchanged precipitation, a dying canopy will have lower interception as needles fall, although the mechanisms that control needle fall remain unclear (Winkler, Boon, Zimonick, & Baleshta, 2010). Falling needles simultaneously allow more shortwave incident energy to penetrate the forest canopy, decreasing the albedo of snow and increasing its ability to absorb shortwave radiation (Pugh & Small, 2012; Winkler et al., 2010).

MPB infected watersheds produce post-epidemic increases in annual water yields with an advanced hydrograph (Potts, 1984). Relatively few studies have taken a mechanistic approach to studying the multiple factors relating to snow accumulation and ablation that can be altered by MPB infestation (but see Boon, 2009; Pugh & Small, 2012). MPB damaged canopies undergo characteristic ‘red’ and ‘gray’ stages of death as trees are killed and lose needles over the course of several years (Safranyik and Wilson, 2007). Changes to snow accumulation and ablation following MPB damage can be understood by extending a conceptual model introduced by Pugh and Small (2012) (Figure 1). A dying canopy will accumulate less snow, absorb less incident shortwave radiation, absorb less momentum from the atmosphere (with a corresponding increase in subcanopy wind speeds), and serve as a less effective ‘thermal blanket’ against longwave

radiation loss than an unfested canopy, all else being equal. The relative importance of these changes to the canopy, especially during the red phase, on the energy balance of snow during the melt period remains unquantified.

These mechanisms and others which govern snow accumulation and melt in forests can be described by a linear one dimensional snow energy balance model (Link & Marks, 1999; Marks & Dozier, 1992) where Q_m , the total energy transfer to the snow (in $W\ m^{-2}$) is a function of the net radiation R_n plus sensible heat flux (H), latent heat flux (λE), and soil heat flux (G):

$$Q_m = R_n + H + \lambda E + G \quad (1.1)$$

and where R_n can also be defined as the incident incoming short wave radiation (SW_{in}) minus the outgoing short wave radiation (SW_{out}), reflected by snow, plus the incoming longwave radiation (LW_{in}) minus the outgoing longwave radiation emitted by the surface (LW_{out}):

$$R_n = SW_{in} - SW_{out} + LW_{in} - LW_{out} \quad (1.2)$$

SW_{in} radiation includes portions of the electromagnetic spectrum in the range between *ca.* 300 and 2800 nm. LW_{in} includes bandwidths beyond the shortwave bands to *ca.* 50000 nm. H and λE are the net turbulent exchange that account for conduction and evapotranspiration, and G is the energy exchange between the soil surface and the snow.

Snowmelt in forests caused by snow energy gain is attributed mostly to the flux of solar and thermal radiation (Bewley, Alila, & Varhola, 2010; Link & Marks, 1999; Marks & Dozier, 1992) which is strongly related to the state of the canopy (Winkler 2010). SW_{in} increases with decreased forest cover due to larger canopy gap fractions (Ellis &

Pomeroy, 2007). The forest canopy acts not only to shade the snow from incident solar radiation, but also alters the snowpack albedo by contributing litter to the snow surface. The most important physical parameters that contribute to snow albedo are snow grain size and snow impurities (Aoki, 2003) and increases in impurities such as tree litter decrease albedo (Warren & Wiscombe, 1980). Previously covered needles progressively decrease the reflective properties of snow as it melts and these needles become exposed at the snow surface (Winkler, 2010).

Contribution from the near infrared, or longwave spectrum (LW) to snow packs was investigated by Pomeroy et al. (2009) who found that a decrease in canopy density led to daytime heating of tree trunks with shortwave radiation and thereby the emission of more energy to the snowpack in the form of LW_{in} . Still, the LW contribution to the overall energy budget to the snowpack has been found by previous studies to be minor compared to the shortwave component (Link & Marks, 1999; Marks & Davis, 1992; Marks & Winstral, 2001), suggesting that the dominant contributions to changes in R_n after MPB attack will come from changes to SW_{in} and SW_{out} rather than changes to LW_{in} and LW_{out} , noting that the snow surface should remain at or near 0 °C during the melt period regardless of MPB disturbance such that any changes to LW_{out} will be minor.

H and λE tend to comprise a smaller amount of total energy flux to and from the snowpack during the melt period than SW and LW (Boon, 2009; Marks & Davis, 1992) although some studies on clearcut and non-forested systems point to an important role of H in driving snow ablation (Marks & Winstral, 2001). H is defined as the transfer of heat

energy from the snowpack to the atmosphere by conduction and convection and can be written using the bulk aerodynamic method:

$$H = \rho_a C_p C_h u_a (T_a - T_{ss}) \quad (1.3)$$

where ρ is the density of air, C_p is the heat capacity of air, T_{ss} is the aerodynamic snow surface temperature, T_a is the air temperature, and C_{hn} is the bulk transfer coefficient for sensible heat under a neutral stability atmosphere, $C_{hn} = k^2 [\ln(z_a / z_o)]$, u_a is wind speed at height z_a , k is the von Kármán constant (0.4), and z_o is the aerodynamic roughness length for the snow surface in m. Wind, surface roughness and the stability of air all play a role in H by altering C_h .

H can be measured with the eddy covariance approach using:

$$H = \rho C_p \overline{w'\theta'} \quad (1.4)$$

where w is vertical wind velocity, θ is potential temperature, primes represent deviations from the mean and the overbar is the averaging operator.

λE is evapotranspiration, or water vapor exchange between surface to atmosphere, and includes in the case of snowmelt, the loss of energy to the latent heat of vaporization and the latent heat of sublimation. Condensation or sublimation of water vapor onto the snowpack can also occur, which represents an energy gain by snow (DeWalle & Rango, 2008). λE can be defined using by using the bulk aerodynamic equation following Kustas et al. (1994):

$$\lambda E = p_a \lambda_v C_e \frac{0.622}{P_a} (e_a - e_{ss}) \quad (1.5)$$

and

$$C_{en} = C_{hn} = k^2 [\ln(z_a / z_o)] \quad (1.6)$$

where ρ_a is the density of air, λ_v is the latent heat of vaporization or sublimation, C_e is the bulk transfer coefficient for vapor exchange, C_{en} is the bulk transfer coefficient for vapor exchange under neutral stability P_a is total atmospheric pressure, e_a is the vapor pressure of ambient air, and e_{ss} is vapor pressure at the snow surface. λE can be measured using the eddy covariance approach using

$$\lambda E = \overline{\rho q'w'}$$

where q is water vapor concentration .

Tenderfoot Creek Experimental Forest General Description

Data analysis and modeling efforts were performed using data obtained from measurements and readings taken from the watershed that comprises of Tenderfoot Creek Experimental Forest (TCEF). TCEF was established in 1961 as an experimental forest for watershed research, but its scope expanded over the years to study fisheries, fire history, animal communities, and vegetation composition. Research was designed with the purpose of developing and evaluating methods to manage Eastern Slope Lodgepole pine forests communities for sustainable production and biodiversity. Farnes (1995) reported that nearly 98 percent of TCEF had been burned in the last 300 years, but only 5 percent had burned in the last 90 years due to fire suppression (Farnes, 1995).

The geology of the area includes igneous intrusive sills of Wolesy shale, granitic gneiss, Flathead quartzite and quartz porphyry (Schmidt & Friede, 1996). Glaciation formed the landscape's large basins with the streams regaining a dendritic pattern, of

which the Tenderfoot Creek has carved the deepest and steepest canyon with prominent bedrock outcroppings (Mincemoyer & Birdsall, 2006). Tributaries become more incised as they approach the main stem of Tenderfoot Creek (Jencso & McGlynn, 2011)

Unlike the characteristic MPB attacks found in British Columbia and other parts of Montana, where large tracks of homogeneous stands are infested, (Kurz et al., 2008) the recent MPB infestation in TCEF has remained small and intermittent as of Summer 2010, and has slowly spread. A study by Kaiser, et al. (2012) used a three component mixing model of spectral indices applied to high resolution remote sensing images (Quickbird) in combination with LiDAR data to better understanding the current beetle outbreak in TCEF (Kaiser, McGlynn, & Emanuel, 2012). Kaiser's study found that approximately 2% of vegetation above 3m in height were in the red stage indicating a more nascent or endemic form of attack.

SNOTEL General Description

Snowpack Telemetry systems (SNOTEL) have been operating in mountain regions in the United States since the mid 1970s (Nault & Eastlund, 2006). Over 750 automated SNOTEL systems have been installed, operated and maintained by the NRCS. The standard SNOTEL station measures air temperature through a shielded thermistor, precipitation via a storage type gage with a perforated windshield, snow water content (SWE) via a snow pillow filled with an anti-freezing agent and a pressure transducer, and snow depth with a sonic sensor. Enhanced SNOTEL sites often additionally include barometric pressure, relative humidity, soil moisture, soil temperature, solar radiation, and wind speed and direction. All data is relayed through meteor burst communications

technology to three master stations near Ogden, Utah; Boise, Idaho; and Anchorage, Alaska. The technology allows for data to become available near real time. Data and reports and forecasts are made available to the public via the NRCS website (www.wcc.nrcs.usda.gov). The NRCS operates over 90 SNOTEL sites in Montana. Two of these sites Onion Park SNOTEL and Stringer Creek SNOTEL provide upper and lower elevation meteorological data for this study.

Study Objectives

The objective of this study is to investigate how a stand impacted by MPB alters the factors that drive snow melt. I used meteorological data, snowpack observations, and modeling at a clearcut, homogenous green stand, heterogeneous green stand, and a MPB infected red stand to make comparisons of snow energy dynamics over melt periods of one high snow year and one average snow year. A suite of meteorological sensors in the homogenous green, lodgepole pine stand provided measurements of each term in the snow energy balance with which to guide comparisons against other sites. A clearcut site also provided measurements to provide insight on how clearcut practices alter snowpacks, and effectively defined meteorological inputs that are not affected by a canopy. The red stand and heterogeneous green stand were used to analyze change over time relative to the clearcut and homogenous green site. Comparisons of meteorological and snowpack time series data of were made to determine the effects that a canopy can have on snow melt timing and the intensity to which ablation occurs. This provided further insight to current model predictions and the ability to critique new model

possibilities. Cumulative energy gains and average rate of energy gain per day over each sites' corresponding melt period was referenced against other sites to identify change from the 2011 to 2012.

Figures

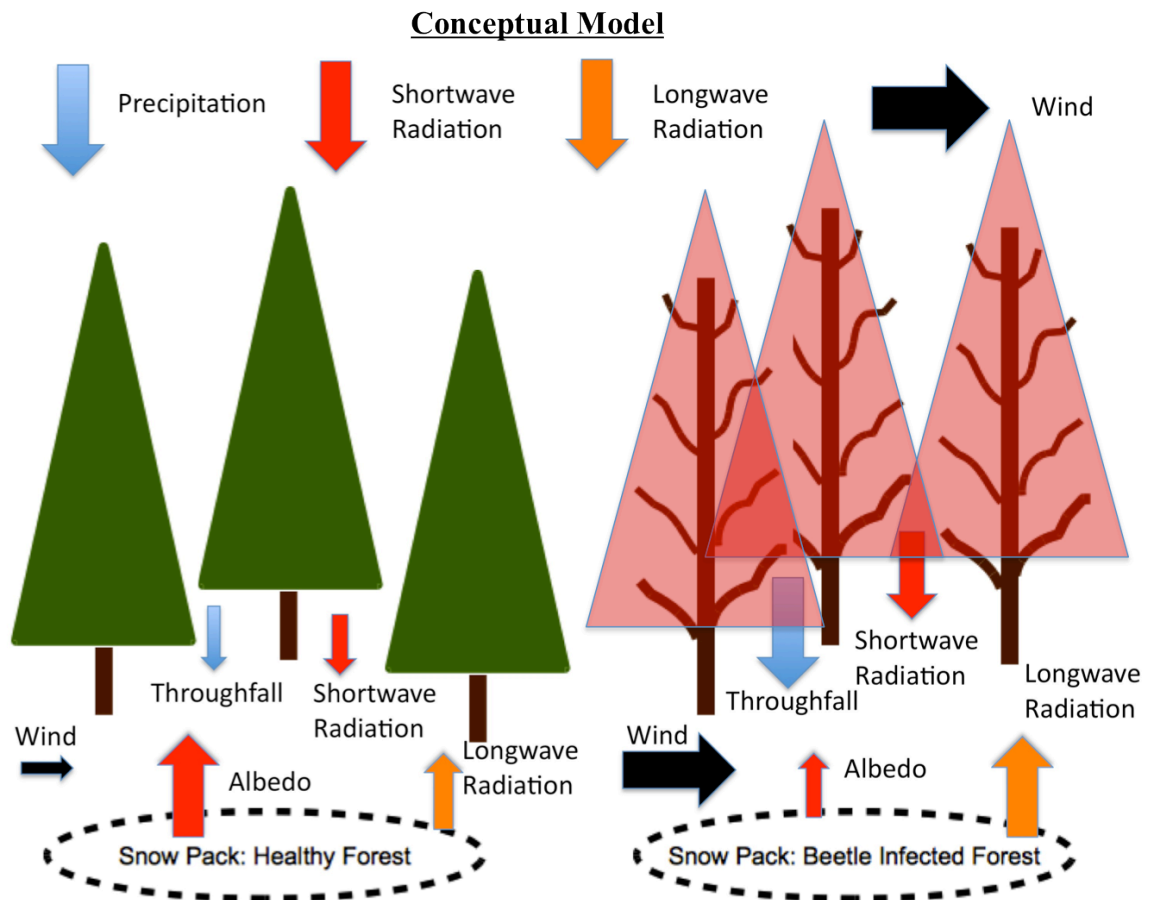


Figure 1: Components that impart a physical influence on snow energy dynamics. A canopy reduced by MPB is likely to experience increased transmission of SW_{in} , while the more open sky is likely to increase LW_{out} . Additionally, throughfall is likely to increase due to the lower stem density for interception.

REFERENCES CITED

- Aguado, E. (1985). Radiation Balances of Melting Snow Covers at an Open Site in the Central Sierra Nevada, California. *Water Resources Research*, 21(11), 1649–1654.
- Amman, G. D. (1977). The role of the mountain pine beetle in lodgepole pine ecosystems: impact on succession. In *The role of arthropods in forest ecosystems* (pp. 3-18). Springer Berlin Heidelberg.
- Aoki, T. (2003). Effects of snow physical parameters on shortwave broadband albedos. *Journal of Geophysical Research*, 108(D19), 1–12. doi:10.1029/2003JD003506
- Aukema, B. H., Carroll, A. L., Zheng, Y., Zhu, J., Raffa, K. F., Dan Moore, R., Stahl, K., et al. (2008). Movement of outbreak populations of mountain pine beetle: influences of spatiotemporal patterns and climate. *Ecography*, 31(December 2007), 348–358. doi:10.1111/j.2007.0906-7590.05453.x
- Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066), 303–9. doi:10.1038/nature04141
- Bewley, D., Alila, Y., & Varhola, A. (2010). Variability of snow water equivalent and snow energetics across a large catchment subject to Mountain Pine Beetle infestation and rapid salvage logging. *Journal of Hydrology*, 388, 464–479. doi:10.1016/j.jhydrol.2010.05.031
- Boon, S. (2009). Snow ablation energy balance in a dead forest stand, 23(January), 2600–2610. doi:10.1002/hyp
- Cayan, D. R. (1996). Interannual Climate Variability and Snowpack in the Western United States. *Journal of Climate*, 9(5), 928–948.
- Cole, W. E., & Amman, G. D. (1969). Mountain pine beetle infestations in relation to lodgepole pine diameters (Vol. 95). US Dept. of Agriculture, Forest Service, Intermountain Forest & Range Experiment Station.
- Denitto, G., Egan, J., Lockman, B., Sontag, S., Brytten, S., Sturdevant, N., & Gannon, A. (2011). *Montana Forest Insect and Disease Conditions and Program Highlights - 2011*.
- DeWalle, D. R. (School of F. R. at the P. S. U., & Rango, A. (USDA A. R. S. (2008). *Principles of Snow Hydrology* (p. 165). Cambridge University Press.

- Dominguez, F., Rivera, E., Lettenmaier, D. P., & Castro, C. L. (2012). Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models. *Geophysical Research Letters*, 39(5), 1–7. doi:10.1029/2011GL050762
- Ellis, C. R., & Pomeroy, J. W. (2007). Estimating sub-canopy shortwave irradiance to melting snow on forested slopes, 21, 2581–2593. doi:10.1002/hyp
- Emanuel, R. E., Epstein, H. E., McGlynn, B. L., Welsch, D. L., Muth, D. J., & D’Odorico, P. (2010). Spatial and temporal controls on watershed ecohydrology in the northern Rocky Mountains. *Water Resources Research*, 46(11), 1–14. doi:10.1029/2009WR008890
- Emanuel, R. E., Riveros-Iregui, D. a., McGlynn, B. L., & Epstein, H. E. (2011). On the spatial heterogeneity of net ecosystem productivity in complex landscapes. *Ecosphere*, 2(7), art86. doi:10.1890/ES11-00074.1
- Essery, R., Pomeroy, J., Ellis, C., & Link, T. (2008). Modelling longwave radiation to snow beneath forest canopies using hemispherical photography or linear regression, 2800(June), 2788–2800. doi:10.1002/hyp
- Farnes, P. E., Shearer, R. C., McCaughey, W. W., & Hanson, K. J. (1995). *Comparisons of Hydrology, geology, and Physical Characteristics between Tenderfoot Creek Experimental Forest (East Side) Montana, and Coram Experimental Forest (West Side) Montana* (pp. 1–20).
- Gryning, S.-E., Batchvarova, E., & De Bruin, H. A. R. (2001). Energy balance of a sparse coniferous high-latitude forest under winter conditions. *Boundary-Layer Meteorology*, 99, 465–488.
- Hardy, J. P., Davis, R. E., Jordan, R., Li, X., Woodcock, C., & Ni, W. (1997). Snow ablation modeling at the stand scale in a boreal jack pine forest, 102(96), 397–405.
- Hardy, J. P., Melloh, R., Robinson, P., & Jordan, R. (2000). Incorporating effects of forest litter in a snow process model. *Hydrological Processes*, 3237(September), 3227–3237.
- Harestad, A. S., & Bunnell, F. L. (1981). Prediction of snow-water equivalents in coniferous forests. *Canadian Journal of Forest Research*, 11(4), 854-857.
- Jencso, K. G., & McGlynn, B. L. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research*, 47(11), 1–16. doi:10.1029/2011WR010666

- Jessie, E., Carroll, A. L., & Taylor, S. W. (2003). Effect of climate change on range expansion by the mountain pine beetle in British Columbia.
- Kaiser, K. E., McGlynn, B. L., & Emanuel, R. E. (2012). Ecohydrology of an outbreak: mountain pine beetle impacts trees in drier landscape positions first. *Ecohydrology*, n/a–n/a. doi:10.1002/eco.1286
- Kustas, W.P., Rango, A., and Uijlenhoet, R. (1994) A simple energy budget algorithm for the snowmelt runoff model. *Water Resources Research*, 30(5), 1515-27
- Kurz, W. a, Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, a L., Ebata, T., et al. (2008). Mountain pine beetle and forest carbon feedback to climate change. *Nature*, 452(7190), 987–90. doi:10.1038/nature06777
- Lee, X., Finnigan, J., & Paw U, K. (2005). Coordinate systems and flux bias error. *Handbook of Micrometeorology*, 33–66.
- Link, T. E., & Marks, D. (1999). Point simulation of seasonal snow cover dynamics beneath boreal forest canopies ESC-30, 104, 841–857.
- Logan, J. A., & Powell, J. A. (2001). Ghost Forests, Global Warming, and the Mountain Pine Beetle (Coleoptera : Scolytidae). *American Entomologist*, 47(3), 160–173.
- Marks, D., & Davis, E. (1992). Climate and Energy Exchange at the Snow Surface in the Alpine Region of the Sierra Nevada Measurements and Monitoring. *Water Resources Research*, 28(11), 3029–3042.
- Marks, D., & Dozier, J. (1992). Climate and Energy Exchange at the Snow Surface in the Alpine Region of the Sierra Nevada 2 . Snow Cover Energy Balance. *Water Resources Research*, 28(11), 3043–3054.
- Marks, D., & Winstral, A. (2001). Comparison of Snow Deposition , the Snow Cover Energy Balance , and Snowmelt at Two Sites in a Semiarid Mountain Basin. *Journal of Hydrometeorology*, 2(3), 213–227.
- Mauder, M., & Foken, T. (2004). *Documentation and instruction manual of the eddy covariance software package TK2* (Vol. 26). Univ., Abt. Mikrometeorologie.
- Mincemoyer, S. A., & Birdsall, J. L. (2006). VASCULAR FLORA OF THE TENDERFOOT CREEK EXPERIMENTAL FOREST , LITTLE BELT MOUNTAINS , MONTANA, 53(3), 211–222. doi:10.3120/0024-9637(2006)53

- Mitton, J. B., & Ferrenberg, S. M. (2012). Mountain pine beetle develops an unprecedented summer generation in response to climate warming. *The American naturalist*, 179(5), E163–71. doi:10.1086/665007
- Molotch N. P., (2009) Reconstructing snow water equivalent in the Rio Grande headwaters using remotely sensed snow cover data and a spatially distributed snowmelt model. *Hydrological Processes* 23:7, 1076-1089
- Moncrieff, J. B., Massheder, J. M., De Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., et al. (1997). A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. *Journal of Hydrology*, 188, 589–611.
- Moncrieff, J., Clement, R., Finnigan, J., & Meyers, T. (2005). Averaging, detrending, and filtering of eddy covariance time series. In X. Lee, W. Massman, & B. E. Law (Eds.), *Handbook of Micrometeorology* (pp. 7–31). Springer.
- Nault, B., & Eastlund, R. (2006). *Snow Survey & Water Supply Forecasting Program* (pp. 1–4).
- Nippgen, F., McGlynn, B. L., Marshall, L. a., & Emanuel, R. E. (2011). Landscape structure and climate influences on hydrologic response. *Water Resources Research*, 47(12), 1–17. doi:10.1029/2011WR011161
- Pacific, V. J., Jencso, K. G., & McGlynn, B. L. (2010). Variable flushing mechanisms and landscape structure control stream DOC export during snowmelt in a set of nested catchments. *Biogeochemistry*, 99(1-3), 193–211. doi:10.1007/s10533-009-9401-1
- Pacific, V. J., McGlynn, B. L., Riveros-Iregui, D. a., Welsch, D. L., & Epstein, H. E. (2011). Landscape structure, groundwater dynamics, and soil water content influence soil respiration across riparian-hillslope transitions in the Tenderfoot Creek Experimental Forest, Montana. *Hydrological Processes*, 25(5), 811–827. doi:10.1002/hyp.7870
- Palmer, P. L. (1988). The SCS snow survey water supply forecasting program: Current operations and future directions. *Proc. Western Snow Conf., Kalispell*, 43 –51.
- Podmeroy, J. W., Marks, D., Link, T., Ellis, C., Hardy, J., Rowlands, A., & Granger, R. (2009). The impact of coniferous forest temperature on incoming longwave radiation to melting snow, 2525(May), 2513–2525. doi:10.1002/hyp
- Pomeroy, J. W., Gray, D. M., Hedstrom, N. R., & Janowicz, J. R. (2002). Prediction of seasonal snow accumulation in cold climate forests. *Hydrological Processes*, 16(18), 3543–3558. doi:10.1002/hyp.1228

- Potts, D. (1984). Hydrologic impacts of a large-scale mountain pine beetle Epidemic. *Water Resources Bulletin*, 20(3), 373–377.
- Pugh, E., & Small, E. (2012). The impact of pine beetle infestation on snow accumulation and melt in the headwaters of the Colorado River. *Ecohydrology*, 5(4), 467–477. doi:10.1002/eco.239
- Raffa, K. F., Aukema, B. H., Bentz, B. J., Carroll, A. L., Hicke, J. a., Turner, M. G., & Romme, W. H. (2008). Cross-scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. *BioScience*, 58(6), 501. doi:10.1641/B580607
- Riveros-Iregui, D. a., & McGlynn, B. L. (2009). Landscape structure control on soil CO₂ efflux variability in complex terrain: Scaling from point observations to watershed scale fluxes. *Journal of Geophysical Research*, 114(G2), 1–14. doi:10.1029/2008JG000885
- Riveros-Iregui, D. a., McGlynn, B. L., Emanuel, R. E., & Epstein, H. E. (2012). Complex terrain leads to bidirectional responses of soil respiration to inter-annual water availability. *Global Change Biology*, 18(2), 749–756. doi:10.1111/j.1365-2486.2011.02556.x
- Riveros-Iregui, D. a., McGlynn, B. L., Marshall, L. a., Welsch, D. L., Emanuel, R. E., & Epstein, H. E. (2011). A watershed-scale assessment of a process soil CO₂ production and efflux model. *Water Resources Research*, 47, 1–12. doi:10.1029/2010WR009941
- Roe, A. and Amman, G. (1970). Mountain pine beetle in lodgepole pine forests. USDA Forest Service, Intermountain Research Station, Research Paper INT-71, 26 pp.
- Safranyik, L., Carroll, A. L., & Wilson, B. (2007). The biology and epidemiology of the mountain pine beetle in lodgepole pine forests. The mountain pine beetle: a synthesis of biology, management and impacts on lodgepole pine, 3-66.
- Samman, S. and Logan, J. (2000). Assessment and response to bark beetle outbreaks in the Rocky Mountain area. Report to Congress from Forest Health Protection, Washington Office, Forest Service, USDA. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-62, 46 pp
- Schmidt, W. C., & Friede, J. L. (1996). Experimental Forests , Ranges , and Watersheds in the Northern Rocky Mountains : A Compendium of Outdoor Laboratories in Utah, Idaho, and Montana.

- Varhola, A., Coops, N. C., Weiler, M., & Moore, R. D. (2010). Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*, 392(3-4), 219–233. doi:10.1016/j.jhydrol.2010.08.009
- Warren, S. G., & Wiscombe, W. J. (1980). A Model for the Spectral Albedo of Snow. II: Snow Containing Atmospheric Aerosols. *Journal of the Atmospheric Sciences*, 37, 2734–2745.
- Winkler, R., Boon, S., Zimonick, B., & Baleshta, K. (2010). Assessing the effects of post-pine beetle forest litter on snow albedo. *Hydrological Processes*, 24(6), 803–812. doi:10.1002/hyp.7648
- Wood, D. L. (1982). The role of pheromones, kairomones and allomones in the host selection and colonization behavior of bark beetles. *Annual Reviews of Entomology*, 27(411-46), 411-445
- Woods, S. W., Ahl, R., Sappington, J., & McCaughey, W. (2006). Snow accumulation in thinned lodgepole pine stands, Montana, USA. *Forest Ecology and Management*, 235(1-3), 202–211. doi:10.1016/j.foreco.2006.08.013

CHAPTER 2

THE IMPACTS OF MOUNTAIN PINE BEETLE ON FORESTED
SNOWPACKS: ACCUMULATION AND ABLATIONAbstract

Mountain snowpacks provide most of the annual discharge of western U.S. rivers, but the future of water resources in the western U.S. is tenuous, as climatic changes have resulted in earlier spring melts that have exacerbated summer droughts. Compounding changes to the physical environment are biotic disturbances including that of the Mountain Pine Beetle (MPB), which has decimated millions of acres of western North American forests. At the watershed scale, MPB disturbance is known to increase the peak hydrograph, and at the stand scale, the 'gray' phase of MPB canopy disturbance is known to decrease canopy snow interception, increase snow albedo, increase net shortwave radiation and decrease net longwave radiation. Fewer studies have been conducted on the red phase of MPB disturbance. We measured the energy balance of four snowpacks, one under a clearcut, a homogenous lodgepole pine green stand, a mixed coniferous green stand, and a MPB infected red stand in the Tenderfoot Creek Experimental Forest in west-central MT. Increases of incoming shortwave radiation were seen in an infested stand relative to a reference clearcut over two years. The clearcut was found to have the highest snow albedo, but the snowpacks of the infested mixed stand had albedo values similar to a nearby healthy mixed coniferous stand. The homogenous lodgepole pine stand had albedo values that were higher than the mixed and infested stands. Net

longwave radiation differed little among stands, but was lower at the clearcut, suggesting that the thermal function of the canopy in the early stages of the red phase is similar to uninfested stands. Turbulent fluxes were also modeled and then compared to measured data provided through the eddy-covariance method under the homogenous lodgepole pine canopy.

Introduction

Mountain snowpacks provide up to 75% of the annual discharge of major rivers in the western United States (Cayan, 1996; Palmer, 1988). The future of water resources in the western U.S. is tenuous, as climatic changes have resulted in earlier spring melts that have exacerbated summer droughts (Westerling et al., 2006). Water management strategies are changing as a consequence; by 2050, peak spring melt runoff in the western U.S. is predicted to occur one month earlier (Barnett, Adam, & Lettenmaier, 2005). Many current dams and reservoirs will be unable to accommodate this seasonal shift, and less water will be available in late summer and fall, when water scarcity is most prevalent (Barnett et al., 2005). Meanwhile, extreme winter precipitation events are likely to increase in intensity (Dominguez, Rivera, Lettenmaier, & Castro, 2012), suggesting that measuring and modeling the accumulation and ablation of snow across years with typical and enhanced precipitation can assist our understanding of likely future hydrologic scenarios in the western U.S.

Associated with climate changes to the physical environment are alterations to the biological environment via the massive outbreaks of the Mountain Pine Beetle (*Dendroctonus ponderosae*) (MPB) and other herbivores that have devastated several

million hectares in western North America (Kurz et al., 2008; Raffa et al., 2008). The MPB has shown an increase in habitat to areas of higher elevation in response to climate change (Aukema et al., 2008; Jessie, Carroll, & Taylor, 2003; Logan & Powell, 2001) and even a shift from univoltine to multivoltine breeding cycles (Mitton & Ferrenberg, 2012). Over 100 trees can be killed per acre per year over a period of three to four years (Samman & Logan, 2000) leaving in their wake a forest, and a snowpack, transformed.

Snow deposition and ablation are a function of topography and vegetation cover (Marks & Winstral, 2001) and are controlled in part by wind scouring, solar radiation flux, and snow interception, all which are closely tied to forest canopy structure (Harestad and Bunnell, 1981). Varhola et al. (2010) found that 57% of the variance of relative changes in snow accumulation, and 72% of the variance of relative changes in snow ablation, can be explained by changes in forest cover. Decreases in canopy cover attenuate snow interception by the canopy, which is subject to sublimation from the canopy. This results in increases of snow accumulation to the underlying snowpack (e.g. Pomeroy, Gray, Hedstrom, & Janowicz, 2002, Varhola, Coops, Weiler, & Moore, 2010). Molotch, et al. (2009) reported a 29% increase in snow accumulation in open versus under-canopy sites.

MPB infected watersheds produce post-epidemic increases in annual water yields with an advanced hydrograph (Potts, 1984), but relatively few studies have taken a mechanistic approach to studying the multiple factors relating to snow accumulation and ablation that can be altered by MPB infestation. MPB damaged canopies undergo characteristic ‘red’ and ‘gray’ stages of death as trees are killed and lose needles over the

course of several years (Safranyik and Wilson, 2006). Changes to snow accumulation and ablation following MPB damage can be understood using a conceptual model following Pugh and Small (2012) (Figure 1). A dying canopy will accumulate less snow, absorb less incident shortwave radiation, absorb less momentum from the atmosphere (with a corresponding increase in subcanopy wind speeds), and serve as a less effective ‘thermal blanket’ against longwave radiation loss than an uninfested canopy, all else being equal. Enhanced litterfall from dying canopies is likely to decrease the albedo of snow and its ability to absorb shortwave radiation (Pugh & Small, 2012; Winkler et al., 2010). The relative importance of these changes to the canopy, especially during the red phase, on the energy balance of snow during the melt period remains unquantified. An improved understanding of water resources will result from understanding the mechanisms that underlie changes to water yield under simultaneous changes to the physical and biological environment.

Objectives

Recent studies on the impacts of MPB disturbance on snow found increased accumulation and ablation rates in stands affected by beetle infestation (Boon, 2009; Pugh & Small, 2012), but differed in methodological design. Boon (2009) continuously measured components of the energy balance in three plots in interior British Columbia: a clearcut site and two pine stands, one healthy, and one in the gray stage with dead, needleless trees following MPB disturbance. Pugh and Small (2012) studied eight pairs of red-stage infested and healthy plots near the headwaters of the Colorado River. No studies to date have continuously measured the energy balance of snow in healthy,

clearcut, and red-stage infested stands, and included the turbulent exchange of sensible and latent heat flux between snow and atmosphere, across the melt period over multiple years.

I investigated change in a red stand's attenuation of SW_{in} over time compared to a reference subcanopy site and clearcut site. Additionally, I made a direct comparison in 2012 with attenuation of SW_{in} at an adjacent, healthy, mixed stand. An increase in SW_{in} from 2011 to 2012 relative to the subcanopy and clearcut site would signal a defoliating canopy that would allow more SW_{in} to be transmitted through the canopy and be available for melt. I explored how a possible change in attenuation in SW_{in} at a red stage stand might compare with a healthy mixed stand to further understand SW_{in} effects on snow melt dynamics in a forest stand that has less transmission of SW_{in} but also lower albedo. A red stand is likely to shed more needles than a healthy homogenous stand, but if this change in albedo resembles or even surpasses that of a mixed stand, a relative change in albedo can be further investigated for spatial investigations in the future. LW_{in} at the red stand is hypothesized to decrease over time, relative to the subcanopy and clearcut, because there will be less foliage to effectively emit LW_{in} to the snow pack and act less as a thermal blanket. The combination of increased transmission of SW_{in} , more effective absorption of SW_{in} into the snowpack via lower albedo, will provide more energy for melt at the red stand than a healthy stand, but whether a significant decrease in LW_{in} emission will offset this increase is another question that I address.

I also use measured turbulent fluxes under the forest canopy to find over- or under-predicted losses and gains of energy to a snow pack via latent and sensible heat

fluxes. This provides further insight to current model predictions and the ability to critique new model possibilities.

Methods

Study Location and Characteristics

Tenderfoot Creek Experimental Forest Fieldwork was performed in the Tenderfoot Creek Experimental Forest (TCEF) in Meagher County of west-central Montana. TCEF is part of the United States Forest Service's Lewis and Clark National Forest and encompasses seven gauged watersheds within a 3,693 hectare area that make up the headwaters of Tenderfoot Creek. Elevation ranges from 1,840 to 2,421 meters (Figure 2) with a mean of 2,205 meters (Pacific, McGlynn, Riveros-Iregui, Welsch, & Epstein, 2011). Lodgepole pines make up a large majority of the forest canopy, either as monotypic stands or in mixed coniferous forests with Engelmann spruce (*Picea engelmannii*), whitebark pine (*Pinus albicaulis*), and subalpine fir (*Abies lasiocarpa*). Many areas of TCEF have low species and age class diversity with forest communities dominated by even aged lodgepole pine (Mincemoyer & Birdsall, 2006), and we contrast measurements in an even age lodgepole stand against those in mixed stands with differing degrees of MPB infestation.

Climate conditions are temperate continental with an average annual precipitation of 880 mm and ranges from 594 mm and 1050 mm at the lowest and highest elevations, (Jencso & McGlynn, 2011). About 70 % of TCEF's precipitation occurs between the months of November and May, primarily as snow (Farnes, Shearer, McCaughey, &

Hanson, 1995; Riveros-Iregui et al., 2011). Approximately 550 mm of the average 850 mm of precipitation is lost to evapotranspiration and the mean annual runoff of Upper Tenderfoot Creek is *ca.* 300 mm (Pacific, Jencso, & McGlynn, 2010).

Stringer Forest Site The Stringer Creek watershed within TCEF is a heavily instrumented 300 ha subcatchment (Emanuel et al., 2010). Since 2005, above-canopy meteorological and eddy covariance measurements have been made at 30 m above the ground surface on a 40 meter tower located at N46.9522479 W110.885312 (Emanuel et al., 2010; Emanuel, Riveros-Iregui, McGlynn, & Epstein, 2011; Riveros-Iregui & McGlynn, 2009). Six 80 W solar panels were installed on this tower to power the subcanopy measurement system, in conjunction with a Morning Tristar TS-45 charge controller and four 78 Ah ACG batteries. In the fall of 2010 a three-meter subcanopy tower ('subcanopy') was installed 19 m SSE m of the tall tower at N46.95218 W110.88507 and with an elevation of 2250 that included a full suite of sensors for micrometeorological and energy balance measurements. A Campbell Scientific SR50A-L sonic depth sensor located at 1.75 m above the ground surface measured snow depth. Solar and thermal radiation data were recorded using a NR01 four-component net radiometer with expected daily average accuracy within 10% and a typical sensitivity range of 10 to 40 $\mu\text{V W}^{-1}\text{m}^{-2}$ (Hukseflux, Delft, The Netherlands) at 2.13 m above ground surface. Snow surface temperature was measured by an SI-111 infrared temperature sensor with an absolute accuracy of $\pm 0.2^{\circ}\text{C}$ between -10° and $+65^{\circ}\text{C}$ (Apogee Instruments, Logan, UT) located at the same height. A LI-190 photosynthetically active radiation sensor with a typical sensitivity of $5\mu\text{A per } 1000\mu\text{mol s}^{-1}\text{m}^{-2}$ (LiCor, Lincoln,

NE) was mounted at approximately 2.13m above the ground surface. A CS616 soil moisture probe (Campbell Scientific, Lincoln, NE) was inserted horizontally 5cm below the soil surface. For ground heat flux (G), a self-calibrating HFP01 heat flux plate (Hukseflux) with expected typical accuracy (for 12 hour totals) within +5%/-15% in most common soil, was buried 5cm below the soil surface. Additionally, a HMP45C (Vaisala, Helsinki, Finland) recorded relative humidity and temperature at 2.18 m. All sensors were logged using Campbell CR3000 and CR1000 data loggers that recorded data every minute and stored half-hour averages.

Sensible heat exchange (H) was measured using a CSAT-3 sonic anemometer (Campbell Scientific Inc.) and latent heat exchange (λE) was measured using the eddy covariance technique by coupling the sonic anemometer with an enclosed LI-7200 CO₂/H₂O infrared gas analyzer (LiCor), both at 2 m above the ground surface. The air inlet was located 25 cm northward of, 5 cm eastward of, and 6 cm below the center of the anemometer path, the tube between the air inlet and the Li-7200 was 100 cm, and flow rate was 14.0 L/min. Measurements were collected at 10 Hz and stored on the CR3000 data logger. Axes were rotated for tilt correction using double rotation (Lee, Finnigan, & Paw U, 2005), time series were detrended using block averaging (J. Moncrieff, Clement, Finnigan, & Meyers, 2005), and time lags were detected using covariance maximization (Mauder & Foken, 2004). The analytic correction of high-pass filtering effects (J. Moncrieff et al., 2005) option was selected for the low frequency range and the low-pass filtering option was selected for the high frequency range (J. B. Moncrieff et al., 1997). Spike count/removal options were set allowing for a maximum of 3 consecutive outliers

and the accepted spike level was set at 1.0 %; removed spikes were replaced by linear interpolation.

A 4MP Plantcam (Wingscapes, Alabaster, AL) took photos every 30 minutes from a location approximately 10 m south of the tower and approximately 2.5 m above the ground pointing due north. For a visual reference on snow depth, a one-inch PVC pipe marked every 10 cm was placed in view of the Plantcam.

Spring Park Clearcut Site In the years 1999-2001, tree thinning experiments in separate subcatchments within TCEF were conducted to investigate the effects of different silvicultural treatments on water yield and sediment transport. In the Spring Park subcatchment, a mosaic of clearcut areas of different size lie adjacent to patches lodgepole forest left uncut. Approximately 50% of the basal area in the spring park subcatchment was removed (Nippgen, McGlynn, Marshall, & Emanuel, 2011). A 3m tower, was installed by the former MSU Watershed Hydrology lab in a clearcut within Spring Park at 2221 m asl. A CNR-1 four-component net radiometer (Kipp and Zonen, Delft, The Netherlands) located at approximately 2m above ground measured solar and thermal irradiance. This tower and the previously described sensors are owned operated, and maintained by the MSU Watershed Hydrology Lab. In the fall of 2010, a SR50A-L sonic distance sensor was added 1.65 m above the ground surface to record snow depth. An HFP01 ground heat flux plate was installed 5 cm below the soil surface, and an SI-111 infrared radiometer was secured to a tower arm at 1.7 m to measure snow surface temperature. These sensors were recorded every minute, averaged over 30 minute intervals, and logged by a CR3000 combined with an AMT 25 multiplexer to

accommodate thermocouples. A 4 MP plantcam was installed at the top of the tower, taking photos at 0 degrees N at 30 minute intervals. Power was supplied with five 80 W solar panels which were installed on three meter tall brackets. A TS-45 charge controller regulated power input from the panels to charge four 78 Ah ACG batteries, which directly powered the logger and sensors.

Quartzite Ridge Forest Comparison Site The Quartzite Ridge Forest Comparison site comprised two adjacent stands both at 2289 m asl – one in the red stage of MPB infestation ('infested') and one healthy ('healthy'), separated by 14m at N46.94496 W110.87280 and N46.94508 W110.87289, respectively. The infested stand was in the red stage of beetle infestation, while trees surrounding the healthy stand were green and healthy and saw little sign of MPB impact.

The infested site was installed in March, 2011. It comprised of a small micrometeorological tower made with 2.5 m long, one inch steel pipe stabilized using guy wires connected to rebar stakes that were arranged to minimize interference with instrumentation. A NR01 radiometer, attached at 1.75m, was fixed to record solar and thermal irradiance under the canopy and a LiCor Li-190 measured photosynthetically active radiation at 2 m above the ground surface. A temperature ladder made of one inch PVC was installed with 5 copper-constantan thermocouples mounted at 0, 25, 50, 75 and 100 cm above ground. To install the temperature ladder, a pit had to be dug to the ground, the pipe was stabilized using rebar, and the entire length of the PVC was pushed into the face of the snow pit before re-covering with snow. Thermocouples were controlled by Campbell Scientific AM16/32B multiplexer. All measurements were recorded at five

minute intervals which were averaged every 30 minutes and logged by a CR1000 data logger. Power was supplied by two 10W solar panels that charged two 78 Ah ACG batteries in conjunction with a SunSaver 6L regulator. A 4MP PlantCam® (Wingscapes, Birmingham, AL) was fixed to a tree ~10m south of the tower and oriented at 0 N. In the fall of 2011, a SR50A was fixed to an additional arm on the tower to record snow depth.

The healthy stand tower was installed in November, 2011 as a control to be compared against the infested stand tower. It included all instrumentation found at the infested stand positioned within 5 cm with respect to the ground surface of sensors at the infested stand. The healthy stand was also enhanced with a larger snow temperature ladder consisting of a free-standing 1.5 inch PVC pipe with 5 copper-constantan thermocouples positioned from ground level to 200 cm above ground at 25 cm increments. Additionally, the healthy stand tower was fixed with a Vaisala HMP45C temperature relative humidity sensor (Vaisala, Helsinki, Finland). A PlantCam® was also mounted on a tree 1.75 m to the south of the tower and took half-hourly imagery with a one inch diameter PVC pipe marked every 10 cm for a snow depth reference. Recordings were logged by a CR1000 and AM16/32B combination as well with the 5 minute recordings averaged over one hour intervals. Power was supplied in a similar fashion as the infested stand, but with one 20W solar panel. Table 1 lists instrumentation used at each site for this study.

SNOTEL Two SNOTEL sites began recording data in 1994 within TCEF and include Onion Park, with an elevation of 2258 meters *ca.* approximately 3 km from the infested and healthy sites, and Stringer Creek at 1996 meters near the center of TCEF. Enhanced data collected by these two sites used in the present study include wind speed,

precipitation, snow depth, and SWE. The Stringer SNOTEL site is located <1 km from the Upper Stringer Creek Watershed (Riveros-Iregui, McGlynn, Emanuel, & Epstein, 2012).

Measurements

Stand Comparisons The subcanopy, infested, and healthy stands were each measured for average tree height and diameter at breast height using a Suunto PM-5/1520 Height Meter and a Spencer Products' Original Loggers Tape, respectively.

Snow Surface Temperature Snow Surface Temperature (T_{ss}) was measured using Apogee SI-111 observations at the clearcut and subcanopy sites and calculated using the downward facing pyrgeometer at the infested and healthy sites. T_{ss} was calculated following the Stefan-Boltzmann equation:

$$T_{ss} = \left(\frac{LW_{out}}{A \epsilon_{ss} \sigma} \right)^{.25} \quad 2.1$$

where A is the view factor (set to 1) ϵ_{ss} is the emissivity of the snow surface generally considered to be .97 (Hardy et al., 1997), and σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$). ϵ_{ss} is set to one to match the same assumption made by the SI-111.

Snow Pits. Snow density profiles were performed monthly during the months of December through April in the subcanopy and clearcut sites. Each pit was dug to present a vertical face with a standard avalanche rescue shovel. Using a 1000 cc cutter provided

in the ProSnow Kit II (snowmetrics, Fort Collins, CO), a sample from every 10 centimeters of depth was cut and weighed on a digital scale. The depth of the snowpit was recorded and in the case of depths not factors of ten, the top 10 cm of snow was recorded. Mass of snow in grams was then divided by 1000 cm to achieve density at each corresponding depth.

Snow Tubes/Snow Course Measurements Fifteen snow course transects were identified to cover a range of aspects, elevation, and slope, and were distributed across the watershed and distributed to allow for spatial interpolation of SWE to compare with SNOTEL SWE timeseries (Fabian Nippgen, personal communication). Monthly surveys between February and March 2011 and February of 2012 of all fifteen sites were attempted, with 42 surveys completed. Each survey consisted of ten samples between 0.5 and 1 m apart using a federal Sierra Snow Tube. Depth, and weight of each core was recorded, with cores showing a greater than 30% change in length to depth rejected. In some cases, 30% ratios of depth to core length were not achievable due to snow conditions such as depth hoar, and were noted. If soil or vegetation was present at the bottom of the core, the volume of the impurity was subtracted from the total core length. The impurity was also discarded so as not to be counted when the sample was weighed. Calibrations of weight were made on the empty snow tube before and after each transect. Direction and start points of each transect was recorded by flagging to avoid trampled courses resulting from previous measurements.

Leaf Litter Baskets Twelve 0.5 m^2 leaf litter baskets were spread in groups of four at the healthy, infested, and subcanopy sites, in October, 2011. Litter baskets were made using 2" x 8" pine lumber and fine screen mesh. Legs were attached to the baskets to keep them off the ground and four baskets were positioned randomly within a 20 m radius centered about the tower. Four litter baskets were distributed at three snow courses as well for later reference. Needles were collected after snowmelt, dried, and weighed using an electronic scale with 0.001 g accuracy.

Modeling

Snow Energy Balance The subcanopy site was used as a reference point to measure all energy inputs in the one dimensional model for the snow energy balance (Marks & Davis, 1992; Marks & Dozier, 1992). Energy available to melt a snow pack is described:

$$Q_m = R_n + H + \lambda E + G \quad 2.2$$

where H is the sensible heat flux, λE is the latent heat flux, G is ground heat flux, and the net radiation (R_n) can also be written:

$$R_n = SW_{in} - SW_{out} + LW_{in} - LW_{out} \quad 2.3$$

where SW refers to shortwave radiation, LW refers to longwave radiation, and $_{in}$ and $_{out}$ refer to incident and outgoing radiation fluxes.

Models for Sensible and Latent Heat Flux H and λE were modeled using a bulk transfer formulation following Boon (2009):

$$H = \rho_a C_p C_h u_a (T_a - T_{ss}) \quad 2.3$$

and:

$$C_{hn} = k^2 [\ln(z_a / z_o)] \quad 2.4$$

where ρ_a is the density of air in kg m^{-3} , C_p is the heat capacity of air in $\text{J kg}^{-1} \text{K}^{-1}$, C_h is the bulk transfer coefficient for H (dimensionless), C_{hn} is the bulk transfer coefficient for H for neutral conditions (dimensionless), u_a is wind speed (m s^{-1}) at height z_a (m), z_o is the aerodynamic roughness length for the snow surface (m), k is the von Karman constant (0.40), T_{ss} is the aerodynamic snow surface temperature (K), and T_a is the air temperature (K).

Boon (2009) assumed that the atmosphere was under neutral conditions such that:

$$C_{en} = C_{hn} = k^2 [\ln(z_a / z_o)] \quad 2.5$$

and the bulk aerodynamic equation for calculating latent heat exchange can be written following Kustas et al. (1994):

$$\lambda E = p_a \lambda_v C_e \frac{0.622}{P_a} (e_a - e_{ss}) \quad 2.6$$

C_{en} is the bulk transfer coefficient for vapor exchange, C_{hn} is the bulk transfer coefficient for vapor exchange under neutral stability, λ_v is the latent heat of vaporization or sublimation J kg^{-1} , P_a is atmospheric pressure, e_a and e_{ss} are the air and snow surface vapor pressure in Pa.

In order to distinguish between unstable and stable flow, profile diabatic correction factors can be introduced (Yasuda, 1988). For unstable conditions:

$$\Psi_H = -2 \ln \left[\frac{1 + (1 - 16\xi)^{1/2}}{2} \right]; \quad \Psi_M = .6 \Psi_H \quad 2.7$$

and stable conditions:

$$\psi_M = \psi_H = 6 \ln(1 + \xi)$$

for which the atmospheric stability is defined as:

$$\xi = - \left[\frac{kgzH}{p_a C_p T_a u^{*3}} \right] \quad 2.8$$

where g is gravitational acceleration and z is height (m). H with the diabatic correction factor becomes;

$$H = \frac{.4^2 p_a C_p u_a(z) [T(d + z_H) - T]}{\left[\ln \left(\frac{z - d}{z_M} \right) + \psi_M \right] \left[\ln \left(\frac{z - d}{z_H} \right) + \psi_H \right]} \quad 2.9$$

where d is the zero plane displacement (estimated to be .65 the height of the surface roughness elements), and z , z_M , and z_H are heights above the snowpack at which wind was measured, and can be assumed to be equal because wind flow through snow is minor compared to wind flow through vegetation. The bulk transfer model for sensible heat flux with and without stability corrections are compared against eddy covariance observations at the subcanopy site.

Filters

Snow Depth Snow depth data from all sites during the melt periods of 2011 and 2012 was first filtered based on manufacturer's recommendations about readings with high measurement uncertainty quantified by sensor output. An additional filter was added

to omit readings that were 5cm greater than the previous readings in an attempt to remove obvious spikes. Omitted data were filled by linear interpolation.

Temperature Linear regressions of air temperature were found among the clearcut, infested, subcanopy, and healthy sites against the Onion Park SNOTEL. Temperature observations that exceeded logical bounds of less than -50°C and over 100°C were omitted and gapfilled with calculated temperatures made from these regressions.

Shortwave Radiation SW_{in} observations were frequently compromised by snow accumulation on the pyranometer. Missing SW_{in} observations from the subcanopy, healthy, and infested sites were gapfilled using clearcut SW_{in} measurements in situations where two conditions were met: a) the zenith angle for the sites location was calculated to be less than 90 , indicating daytime conditions, and b) SW_{in} was less than SW_{out} , indicating likely pyranometer snow cover. Gapfilling was performed by finding a simple linear regression between measurements from clearcut site radiometer and observations from the site in question during the melt periods, when snowfall events were infrequent. It was also necessary to account for natural ‘sun flecks’, in which a tree can cast a shadow at an angle, so that the sky facing pyranometer is shadowed while the snow surface underneath may still be reflecting direct sunlight. The data was scanned for periods of 0.5 to 2 hours where SW_{out} was greater than SW_{in} , and were omitted from the filter to capture these naturally occurring events where SW_{net} can be less than zero due to canopy influence. If

SW_{net} was less than zero for periods longer than two hours, it was assumed that the radiometer was covered with snow.

Longwave Radiation LW_{in} and LW_{out} were filtered to omit readings less than 180 W/m^{-2} , corresponding to temperatures below -36 C , which are exceedingly infrequent at TCEF. In 2011, missing LW_{in} observations at the infested stand and clearcut were modeled from the LW_{in} observations at the subcanopy site by establishing a linear relationship between observations from 2012. Data were gapfilled using a regression from the clearcut site, and in the case where clearcut LW_{in} measurements were unavailable, observations from the subcanopy site were used.

Albedo Noontime albedo values were selected for analysis. Filters were applied to the data to ignore large blocks of data (over four readings or two hours) in which SW_{in} was less than SW_{out} resulting in albedo values over one. If four or less readings yielded albedos greater than one, it was assumed that sunflecks were driving this abnormality, in which the upward facing pyranometer was shaded by the canopy but the underlying snow pack still received direct beam shortwave radiation. If over four instances of albedo readings above one were recorded, it was assumed snow was covering the upward facing pyranometer. In these instances, data was gap filled using a regression from the clearcut net radiometer, as its structure and exposure to wind yielded more consistent albedo values less than one.

Soil Heat Flux G under snow is often set to a constant 3.13 W m^{-2} in the absence of measurements (USACE, 1956; Maidment, 1993; Boon 2009). We test this assumption

with G measurements from the subcanopy and clearcut sites, and select representative values from the subcanopy and clearcut sites to model G in the healthy and beetle-infested sites.

Sensible and Latent Heat Eddy covariance-measured H and λE at the subcanopy site was filtered for periods of insufficient turbulence using the friction velocity (u^*) threshold identified by Rains (2013). Periods with a u^* less than 0.05 m/s and turbulent flux measurements less than -10 W/m^2 were gapfilled using equations (2.3) and (2.4), and average wind speed observed for the melt period was used when wind speed measurements were unavailable, following Boon (2010).

Uncertainty Analysis

Significant differences among accumulated energy flux sums were calculated using simple two-sided t-tests assuming a conservative 10% error on radiometric measurements and 15% on eddy covariance observations.

Results

Stand Characteristics

Average dbh was lowest at the healthy stand, reflecting a large contribution of smaller trees, and basal area was lowest at the subcanopy stand, reflecting its homogenous species composition of Lodgepole pine (Table 2). The infested site had the highest basal area and highest level of mortality and MPB presence, likely reflecting the

MPB preference for larger trees. Mortality was highest in the infested stand at 53% of all trees.

Microclimate

Average air temperatures at the Onion Park SNOTEL site were -7 and -6 °C during January 2011 and 2012 and 14 and 15 °C during July 2011 and 2012. Maximum subcanopy site temperature was 27.6 °C and maximum clearcut site temperature was 31.5 °C, both measured on July 18th 2011. Minimum temperatures recorded were -30.5 °C at the subcanopy site and -34 °C at the clearcut site on November 23, 2011. During the melt period in 2011, (Figure 3A) the mean daily averages at the clearcut were higher than the subcanopy site and Onion Park SNOTEL, at 1.6 °C. Stringer Creek had the highest daily average in 2011, at 2.4 °C but sensor malfunction led to missing data that was gap filled for rough comparison purposes. During the melt season of 2012, mean daily average air temperatures were highest at the clearcut, at 4.6 °C and lowest at the infested site, at 2.0 °C (Figure 3B). Average daily temperatures continued to drop below 0 °C well into early June, although for shorter durations. Precipitation at Onion Park (Figure 4) was more common from October through March than other periods, with several notable late spring storms. Summer and early fall saw little precipitation that occurred infrequently. TCEF received measurable precipitation on 149 days in 2011 and 138 days in 2012.

Snow Water Equivalent

SWE was above the 17 year recorded average across most of the snow-covered period at both the Onion Park and Stringer Creek sites in 2011 (Figure 5A). Stringer

Creek had a maximum SWE over 18 cm higher than the 17-year average and Onion Park had maximum SWE nearly 20 cm greater than the 17-year average. Onion Park is at a higher elevation than Stringer Creek and receives more precipitation as snow. Both Onion Park and Stringer Creek indicated maximum SWE events occurring at 21 and 18 days later than average, respectively during 2011. The seasonal patterns of SWE in 2012 were closer to the 17-year average (Figure 5B). Mean SWE from snow tube measurements across TCEF tended to fall between or near Onion Park SNOTEL and Stringer Creek SNOTEL readings during both years. Variability in snow tube SWE measurements across the watershed was a function of mean SWE; larger mean SWE at the SNOTEL sites was positively correlated to higher variability in SWE measured across the watershed.

Snow Depth

Variability in snow depth and melt timing was observed among both SNOTEL sites and the subcanopy and clearcut sites in 2011, with the addition of the healthy and infested site in 2012 (Figure 6 A&B). The Stringer Creek SNOTEL site and the clearcut site had characteristically lower snow depths that melted out earlier during both years, and the Onion Park SNOTEL site had the deepest snow depth which, along with the subcanopy site in 2011, melted out the latest (Figure 6A). In 2012, the infested and healthy sites melted out later than both SNOTEL sites, due in part to a storm adding snow to the snowpack during the melt period (Figure 6B). Complete melt underneath the depth sensors occurred at the Stringer Creek SNOTEL, clearcut, and subcanopy sites before this storm. The infested site consistently had deeper snow than the healthy site, though often

by less than five cm, but complete melt occurred at both sites on day 157 of 2012. Melt periods differed among years, with complete melt occurring on average 27.5 days earlier in 2012 than in 2011 at the clearcut, subcanopy, and SNOTEL sites.

Snow Temperature

Snow temperature at different depths at the infested stand converged to 0 °C on day of year 127 in 2011 (Figure 7A), indicating isothermal conditions. In 2012, the infested site became isothermal 44 days earlier, on day 83 (Figure 7B). The healthy site became isothermal on the same day as the infested stand in 2012. Snow surface temperatures interpolated from air temperatures above the snow pack indicated that cold days and additional snow caused fluctuation in the upper snowpack temperatures until day of year 125 in 2012 (Figure 8).

Patterns in Incident Shortwave Radiation

The slope of cumulative SW_{in} versus time during melt was greater in 2012 by 32% at the clearcut, 39% at the infested site, and 9% at the subcanopy site. 2011 was 1.5 days behind 2012 with cumulative gains of 23 MJ m⁻² of SW_{in} after just two weeks of melt (Figure 9). The infested site received 2% more SW_{in} in 2012 than in 2011 when compared against the clearcut over the same time periods; however, this amounted to cumulative gain of 30.7 MJ m⁻² more energy over the first 15 days of melt. The subcanopy varied little between years during the first two weeks of melt, with .6 MJ m⁻² more in 2011 and less than 1% change in rate of gain. The melt season of 2012 ended with lower cumulative SW_{in} , reflecting the shorter period of melt than that of 2011. Cumulative SW_{out}

displayed less year-to-year variability when compared against common melt periods (Figure 9). However, cumulative totals of SW_{net} at sites displayed important year-to-year variation (Figure 9), again signaling that the addition of snow from the spring storm required a longer melt period at both the infested and healthy sites in 2012. SW_{net} was 39% greater at the subcanopy, 26% greater at the infested, and 61% greater at the clearcut in 2011 than in 2012. However, the slope of Cumulative SW_{net} vs. time in 2011 was 7% lower at the subcanopy, 15% lower in the infested, and 41% lower at the clearcut than in 2012.

The healthy site had the lowest cumulative SW_{in} total, at 67 MJ m^{-2} and the lowest daily gains of SW_{in} and losses of SW_{out} . Yet it required more time to melt out which resulted in a higher total input of SW_{net} over the entire melt period than the subcanopy. Similarly, at complete melt out of the subcanopy site in 2012 (day 120), total SW_{in} was only 5% greater than the infested site. Still, the infested site's melt period extended further into spring, and had a 52% greater cumulative SW_{in} . The clearcut had the highest cumulative SW_{in} at 763 MJ m^{-2} in 2011, but melted soon in 2012 and had a total of only 353 MJ m^{-2} in 2012. SW_{out} was likewise greatest in the clearcut for 2011, as anticipated. Cumulative SW_{net} gains per day during the melt period were greatest at the clearcut site for both years, followed by the subcanopy site in 2011. SW_{net} slopes at the infested were lower in 2011, at 12% less than the subcanopy. However in 2012, cumulative SW_{net} at the infested site during the subcanopy's melt cycle was actually 8% greater. Throughout this period, the infested site's slope indicated greater change in SW_{in} from the previous year than the subcanopy.

Albedo

Albedo values across all sites experienced a steady decrease over 20 days of primary melt out during both years, but began this attenuation 30 days earlier in 2012 (Figure 10). Albedo values periodically increased with fresh snow in 2012, after which complete melt at the subcanopy and clearcut had already occurred. In 2011, both the infested and subcanopy sites had periods of sharp decline in albedo values, compared to more gradual decline in 2012 which is evident in Figures 10A and 10B. Albedo decline at the clearcut was characteristically more similar among both years. During the onset of melt in both years the clearcut had similar values, of .81 in 2011 and .80 in 2012. The rate of decay was indistinguishable, at -.032 per day in 2011 versus -.033 per day in 2012. Albedo at the clearcut site was characteristically higher than the subcanopy and infested sites in 2011, but a statistically significant difference in albedo between the clearcut and subcanopy was not established in 2012. During the melt period in 2011, running average noontime albedo values at the infested site were 27% lower than those found at the clearcut, and 15% lower than those found at the subcanopy site (Figure 10A). Albedo values at all three sites converged toward the later stages of melt after day of year 165 in 2012 (Figure 10B). Change in snow albedo values as melt progressed was depicted by differing slopes from maximas on day of year 148 in 2011, and day of year 120 in 2012 to complete melt.

Longwave Radiation

LW_{in} was positive and nearly equal in slope at the forested sites during the melt period of both years with a mean slope of 27.29 and a standard deviation of 1.27, varying

by at most 7%. The clearcut showed greater year to year variability in LW_{in} with 2012 having a slope 13% of that in 2011 (Figure 11). Slopes for cumulative LW_{out} were similar at all sites over both melt periods and averaged $27.10 \text{ MJ m}^{-2} \text{ d}^{-1}$ with a standard deviation of .25 and differed by 3% at most. At the subcanopy, annual variability led to positive values in 2011 (11.7 MJ m^{-2}) and negative values in 2012 (-4.6 MJ m^{-2}). The clearcut was the only site that was consistently negative (indicating energy loss to the atmosphere) during both melt periods; cumulative LW_{net} summed to -93 MJ m^{-2} in 2011 and -74 MJ m^{-2} in 2012. Variability in LW among years reveals that cumulative LW_{net} totals were less in 2012 than in 2011. Site to site variability point to totals of LW_{net} that were 17.8 MJ m^{-2} at the infested in 2011, but that these differences increased to 26.2 MJ m^{-2} in 2012. Additionally, the healthy stand received 5.3 MJ m^{-2} more LW_{net} than the infested site.

Net Radiation

Annual melt variability showed cumulative totals of R_n are higher in 2011 than in 2012 (Figure 12). Total cumulative R_n at the clearcut was 77 MJ m^{-2} greater, 113 MJ m^{-2} greater in the subcanopy, and 44 MJ m^{-2} higher in 2011 than in 2012. The rate of gain in R_n differed among melt periods as well, with a daily average 7% less in the subcanopy in 2012 than in 2011. However, when normalized for the same time periods, the subcanopy received 32% more R_n in 2012. In the infested site, the rate of gain of R_n increased by 16% in 2012, with a normalized increase of 50%. In the clearcut, average rate of gain per day increased by 33% with normalization over the same time period, which yielded a 60% increase. Inter-site variability confirmed that cumulative R_n at the subcanopy and

infested sites were characteristically lower over time than the clear cut site, with slopes of 18% during the late melt period of 2011. Daily inputs of R_n in the infested site were less than the subcanopy in 2011, but surpassed them in 2012, resulting in not only greater totals over equal timescales, but a visible, comparative change in a MPB infested stand to the radiation component of the snow energy balance.

Latent Heat

Modeled λE , and measured λE at the subcanopy site, were shown to be of considerably less weight as a component of the snow energy balance (Figure 13). Total cumulative λE was more than a full order of magnitude less than R_n . Annual melt period variability demonstrated similar average daily loss of λE and departed among sites by $.02 \text{ MJ m}^{-2}$ per day in 2011 and $.04 \text{ MJ m}^{-2}$ per day in 2012. Site to site variability in λE was limited and demonstrated by an average loss of $.15 \text{ MJ/m}^{-2}$ per day in 2011 and 2012 with a standard deviation of 0.01 and 0.02.

Sensible Heat Flux

Modeled H , and measured H at the subcanopy site, had a much more pronounced effect on Q_m than did λE , and was negative at all sites during both years, yielding energy gains to the snowpacks (Figure 13). Values of cumulative totals of H relative to cumulative totals of R_n were 24% at the infested, 25% at the subcanopy and 35% at the clearcut in 2011. Interestingly, in 2012, values of cumulative totals of H in relation to cumulative totals of R_n became more significant in the subcanopy, at 31%, and less significant at the infested, at 18%. Meanwhile, the clearcut remained about the same.

Slopes of H flux were less positive at the subcanopy and clearcut in 2011 than in 2012.

Alternately, the H flux slope at the infested site was less positive in 2012.

Forested sites were similar, but showed significantly less energy gain to the snowpack through H than the clearcut. H flux slopes of the infested and subcanopy sites are *ca* 65% less than that found at the clearcut in 2011. Similarly, the subcanopy is 57% less than the clearcut in 2012, while the healthy and infested are 43% and 41%, less, respectively.

Ground Heat Flux

G flux was confirmed to be a small factor of the snow energy balance, when compared with R_n , with cumulative totals less than 6 MJ m^{-2} (Figure 13). Annual variability among melt periods for G flux suggested a change at the subcanopy from an energy rise at 0.1 MJ m^{-2} per day in 2011, to slightly decrease, although values were $> 0.01 \text{ MJ m}^{-2}$ per day in 2012. The clearcut showed a 17% decrease in slope from 2011 to 2012 melt periods, such that flux added more energy to the snowpack in 2011.

Among sites, G differed most notably in 2012, in which the G cumulative total became negative at the subcanopy, at -0.1 MJ m^{-2} and remained positive at the clearcut, at 1.53 MJ m^{-2} . The small spike at the end of the melt period was attributed to complete melt of snow over the sensors, while small amounts still resided under depth sensors.

Total Energy

Q_m included all terms of SW , LW , λE , H , G for each site (Figure 14). Annual variability confirmed the decrease in energy inputs needed to melt the lesser snowpack of

2012. During the melt season of both years, the clearcut more rapidly gained Q_m than the forested sites. Average rate of gain of Q_m increased by 55% at the subcanopy in 2012 when normalized over the same time period. The infested site's rate of gain increased by 30% from 2011 to 2012 when normalized, and the clearcut by 80%.

Among sites, the clearcut stand received considerably more total E over the same time period (Figure 14). Sites with canopies showed more similar energy inputs to the snow pack with the infested receiving the most total Q_m . However, during the same time periods in 2011, average gain of Q_m per day at the subcanopy was faster than the infested, but still 90% of the average gain per day at the clearcut. Average gain per day of Q_m at the infested site departed further from the other sites in 2012 and by complete melt at the subcanopy, the infested site had received 22.9 MJ m^{-2} more cumulative Q_m than the subcanopy.

Discussion

The objective of this study is to improve understanding of the early stages of MPB infestation on snow dynamics, and to understand how snow dynamics change across a space-for-time chronosequence of healthy and infested forest plots. I measured the radiation, temperature, depth, and snow temperatures of adjacent healthy and red phase (hereafter 'healthy' and 'infested', respectively) forest plots against two reference plots (one clearcut ('clearcut'), and one homogenous lodgepole pine (*Pinus contorta*) forest ('subcanopy') over a two-year period. These years included one year with snow water equivalent (SWE) significantly greater than the long-term average (2011) and one

year near the long-term average (2012). The clearcut site provided a reference for meteorological inputs uninhibited or enhanced by an overlying canopy and further knowledge in how clearcut practices alter snow melt processes. The subcanopy site is a stand typically ripe for MPB infestation (homogenous and age class) and incorporated a suite of meteorological instruments to measure radiation, depth, relative humidity, temperature, turbulent flux, and ground heat flux to provide a measurements for typical pre MPB infestation conditions. I used measured turbulent flux data of latent and sensible heat provided by an eddy covariance system at the subcanopy site to evaluate predictions made by models using Fourier's Law under similar conditions.

Interannual Variability

More energy was required to melt the larger snowpacks of 2011, and the cumulative sum of Q_m was greater during 2011 than 2012 as a consequence. However, Q_m increased at a greater rate during 2012 due to temperatures that averaged 3 °C higher than 2011 with more clear sky days and greater incident radiation. The dynamics of Q_m are best understood by studying the snowpack of each study site, focusing on the common period during which snow was melting in both 2011 and 2012.

Clearcut Cumulative SW_{in} was greater in the clearcut site during 2012 at a rate of 65 MJ m⁻² per 25 days more than 2011. The cloudier conditions during 2011 resulted in a decrease of global to extraterrestrial radiation ratios and the attenuation of incident radiation available for melt (Aguado, 1985). Average albedo during the onset of melt was similar during both years, 0.80 in 2012 and 0.81 in 2011, and rates of decay were not

statistically different; -0.033 per day in 2012 *versus* -0.032 per day in 2011. However, snowfall events in 2011 occurred during the same days of 2012 that melt was occurring, and delivered fresh, high-albedo snow. As snow ages, it metamorphoses into larger grains and contains more impurities, contributing to lower albedos (Hardy, Melloh, Robinson, & Jordan, 2000; Warren & Wiscombe, 1980; Winkler et al., 2010). Consequently, cumulative totals of SW_{net} was greater in 2011, (Figure 9), but merely due to the longer melt period; the clearcut site gained SW_{net} faster in 2012. Alternately, when considering LW , the clearer skies during 2012 had the opposite effect on Q_m (Pomeroy et al., 2009). During the two-week melt season in 2012, LW_{net} at the clearcut represented a 17.6 MJ m^{-2} (31%) greater loss of energy than the first two weeks of melt in 2011.

Modeled λE varied little among years, and was often negative suggesting condensation and/or sublimation during periods when the vapor pressure of the atmosphere exceeded the vapor pressure of the snow surface (Leydecker and Melack, 1999). The clearcut snowpack in 2011 gained 8% more λE than in 2012 during the initial two weeks of melt (i.e. the entire 2012 melt period), but this difference was less than 0.2 MJ m^{-2} . This suggest that annual variability in λE played a small roll in the snow energy balance. Modeled H likewise differed between 2011 and 2012 due to differences in the T_{ss} / T_a gradient (noting again that 2012 was warmer). Model results indicate that H can comprise a non-trivial component of energy flux, on the order of -50 MJ m^{-2} for example during 2011.

G plays a minor role until during the melt period until the ground surface becomes exposed. Annual variability can be seen, with 17% increase in rate of gain in 2012 over

2011 at the clearcut, likely a result of the ground warming sooner from exposed patches of soil during the more rapid melt out. Boon (2009) set G at $3.13 \text{ W/m}^2/\text{d}^{-1}$; we find a measured mean of $0.65 \text{ W/m}^2/\text{d}^{-1}$ at the subcanopy and $1.1 \text{ W/m}^2/\text{d}^{-1}$ at the clearcut. The cumulative sum of G was 1.5 MJ/m^2 during the first 15 days of melt in 2011 compared with the entire 15 days of melt in 2012, and G accounted for *ca.* 5% of the cumulative sum of Q_m over the melt period during both years.

Subcanopy SW_{in} at the subcanopy site varied little between years when comparing the common melt period. Results are consistent with a greater diffuse fraction of SW_{in} during 2011 that penetrated the canopy more efficiently, resulting in similar cumulative SW_{in} despite less incident above-canopy SW_{in} during 2011. SW_{out} varied little among years during the common melt period, excluding observations during the end of the 2012 melt period when exposed ground resulted in sharply reduced SW_{out} .

Maximum albedo values tended to be higher in 2011, and the addition of snow kept the averages higher throughout the melt period, and SW_{net} was characteristically lower in 2011 than in 2012 during the common melt period as a consequence. Few trees at the subcanopy site succumbed to MPB infestation between 2011 and 2012 (Kinsey, et. al, 2012) and whereas differences in albedo are consistent with increased litterfall during 2011, the mechanisms underlying this likely increase in litterfall are unclear.

In this study, I had the unique opportunity to analyze measured turbulent fluxes of subcanopy λE and H using the eddy covariance method and compare it with models of turbulent flux calculated through the bulk aerodynamic theory. Modeled λE flux was positive during both years, contributing to a loss of energy to the snowpack. Cumulative

λE differed by less than 5% at the clearcut, and less than 1% at the subcanopy and infested sites during the common melt periods of 2011 and 2012. Compared to measured λE at the subcanopy, the modeled cumulative total underestimated snowpack energy loss by 84%, and cumulative totals differed by 7.7 MJ m^{-2} or 11% of cumulative totals of subcanopy Q_m in 2012.

Cumulative sums of modeled H were greater than λE during the common melt period, and comprised 20% of Q_m at the subcanopy in 2011 and 25% during 2012. This suggests H is an important factor to snow melt and is second only to SW_{net} when considering individual components of the snow energy balance. Compared to measurements of H through the eddy covariance, the model under the bulk aerodynamic theory for neutral stability in the atmosphere overestimated measured H by 17 MJ m^{-2} during the 20 day melt period of 2012. Measured sensible heat was found to account for 11% of the total energy for melt in 2012. Unlike model estimates, measurements of turbulent flux at the subcanopy had a net negative energy input to the snowpack, as seen in Figure 23.

Infested SW_{in} at the infested site showed more variability among years than the subcanopy site. SW_{in} was 18% greater in 2012 during the common melt period. This rate of increase between years is greater than that seen at the clearcut, suggesting greater transmission through the canopy in 2012 than in 2011 as a result of MPB damage to the canopy. SW_{out} varied less between years, with less loss during the corresponding melt times in 2012 than in 2011, despite greater inputs of SW_{in} . This suggests that less SW is being reflected in 2012 and instead is being absorbed into the snowpack. Albedo values

confirm this with characteristically lower values in 2012. This is likely due to a combination of: 1. the older age of the surface snow, as less fresh snow fell less often, and 2. increased litter fall found at the subcanopy site (Figure 21). The increase in transmission due to a less foliated canopy, and the increase in albedo, had compounded effects SW_{net} and 2012 had 50% cumulative total Q_m for the same period of melt in 2012 than in 2011.

Cumulative LW_{in} at the infested site was less in 2012 by *ca.* 1% during the common melt period, suggesting that the loss in foliage between years did not affect the canopy's ability to act as a thermal blanket. The point during the MPB damage cycle at which longwave radiation dynamics become pronounced remains unclear and requires additional measurements and models of LW .

Site Variability

Shortwave Radiation Cumulative modeled Q_m increases more drastically over time at the clearcut than the forested sites, which matches well with observations of snow depth. This difference is attributed in part to the lack of forest canopy in decreasing SW_{in} despite the higher albedo of the clearcut snowpack, which is due to the lack of substantial tree litter compared to the forested sites (Hardy et al., 2000; Winkler et al., 2010). Lower snow albedos at the infested site were consequences of greater needle fall than the subcanopy site (Figure 21). In 2012, albedo at the infested site decreased the fastest exemplifying the progressive increase of needles found at different depths being exposed (Winkler et al., 2010). The Healthy site snowpack also had low albedo compared to the

subcanopy site, which can be explained in part by its greater observed biomass. The potential role of mixed vegetation in the infested and healthy sites on decreasing snow albedo *versus* the monotypic Lodgepole pine stand of the subcanopy site needs to be investigated further.

Another possible factor contributing to snow melt and albedo during the melt season was the amount of understory vegetation. As vegetation becomes more exposed to the snow surface, the albedo of the snowpack may become more patchy and have effectively lower values.

Scenario Analysis: Changing Incoming SW To further understand canopy effects on SW_{net} , and consequently the effect clearcuts have on SW_{net} , I applied reduction factors of direct ratios of SW_{in} inputs to the clearcut and made comparisons to the subcanopy and infested sites. In 2011, reduction of 40% of SW_{in} at the clearcut resulted in cumulative readings that closely followed the trends at the forested sites with a total within 10% (Figure 15). The reduction on SW_{in} also reduced SW_{out} , and the consequences on Q_m can be seen in Figure 16. This illustrates the greater role SW_{net} plays in clearings when all the other components are considered.

Scenario Analysis for Albedo As SW_{net} has been seen to be one of the driving forces in providing snowpacks energy for melt, and that canopies have a substantial effect in diminishing SW_{in} , studying albedo would in turn answer the question of diminished SW_{out} . By using running averages of noon-time albedos from all four sites, I was able to compare how albedos found at other sites would change SW_{net} (Figure 19). Greater

energy gains to the subcanopy site are found when albedo values from the infested site are utilized as a surrogate (Figure 20), likely due to the higher amount of organic debris littering the snow. However, earlier melt at the subcanopy site contributes to the steep increase in SW_{net} found at the end of the period, at which it nearly eclipsed SW_{net} totals with simulated albedos.

Longwave Radiation Modeled Q_m becomes positive later in the clearcut site than the forested sites as a consequence in part to lower contributions of LW_{in} . We attribute this to the canopy's enhanced input of LW_{in} from surrounding trees which gain SW during the day and causing the warming of the canopy. The canopy then reradiates this energy in the form of LW . This is consistent with previous studies (Essery, Pomeroy, Ellis, & Link, 2008) and is important when considering comparisons of a MPB infected stand and healthy stand. LW_{out} changes little between sites, as the surface temperature snowpacks across the watershed do not stray far from 0 °C °C. The infested sites higher inputs of LW_{net} compared to the subcanopy site is attributed to its greater basal area. The greater basal area of the healthy stand can explain the higher LW_{net} in comparison to the infested site. Attributing differences of LW_{net} to canopy defoliation would be speculative at this point, as any change in defoliation that has occurred to this point has not produced differences significant enough to separate from the effects of basal area variability among stands. Similar studies (Pugh & Small, 2012) found that the red stage of MPB mortality may cause smaller LW retention and emission, due to loss of moisture in needles, but effects were not observable in the present study.

Scenario Analysis: Changing LW_{net} In another scenario, I analyzed a canopy's effect on decreasing the losses to LW_{net} . I applied multiplying factors to account for the increase in LW_{in} emitted from forest canopies (Figure 17). LW_{out} is largely a function of snow surface temperature, and therefore remained similar across sites. Figure 17 indicates that both forest canopies emit 10% more LW_{in} in 2011 and 20-25% more LW_{in} in 2012. This illustrates the role a clear canopy free sky view has in decreasing LW_{in} . In Figure 18, the 10% increase of LW_{in} in 2011 and the 20% increase of LW_{in} in 2012 were applied to the snow energy balance. Clearly, a lack of LW_{in} plays a major role in attenuating energy for melt in clearcut areas.

Sensible Heat and Latent Heat Modeled turbulent flux attributed to 19% of Q_m in the subcanopy, 20% at the infested, and 26% at the clearcut in 2011. In 2012, the greater difference between the infested site and subcanopy site is likely the result of different heating patterns due to differences in aspect being accentuated during a less cloudy, warmer year. The similarity of H between the healthy and infested sites in 2012 support this in combination with the fact that the gradient between air temperature and snow temperature were the only site specific model inputs. The clearcut demonstrates a stronger gradient in temperature than all of the forested sites, explaining greater gains in H . Wind is likely higher at the clearcut as well, further accentuating gains in H . Further study is necessary to assess the changes to H with regards to alterations in wind speed among beetle impacted forests.

The loss of snowpack energy through λE is attributed to rain on snow events, evaporation, and sublimation. An additional component that should be considered when

studying turbulent fluxes is the canopy's effect on these fluxes by greatly decreasing wind speed. In this initial analysis, wind speed is assumed to be constant among sites. Wind is likely higher at the clearcut further accentuating gains in H , however, the degree to which wind in a red stand is attenuated necessitates further investigation.

Model Assessment for H and λ Models for H flux density were calculated using the bulk aerodynamic theory, which has produced approximations of H flux in snow packs within acceptable error limits (Kustas et al., 1994). However, several simplifying assumptions had to be made (Moore, 1983). In calculating the bulk transfer coefficient for sensible heat, the aerodynamic roughness length (z_0) was estimated at 0.006m, but can range from 0.0002 to 0.02m (Moore, 1983). Due to the relative insensitivity to z_0 in model output, we chose the same value as Boon, 2009, for comparative purposes. Windspeed was measured only at the subcanopy site, and all other sites were given an estimated value of 0.1 m/sec, and thus comparisons of H across sites is highly speculative. Density of air was set at 1.15 kg/m^3 although this is variable to change with elevation and declines with increases in water vapor. Atmospheric Pressure was set at 0.760 kPa, and values within an order of magnitude showed little variability in model output. In this scenario, I assumed that the vapor pressure of the snow surface will be more than the vapor pressure of the air above it (Marks & Dozier, 1992) and that Snow temperature will likely track air temperature as long as air temperature remains below 0°C (Marks & Dozier, 1992).

Models for λE were similarly calculated using the bulk aerodynamic theory, and vapor pressure at the snowpack was assumed to be the saturation vapor pressure at

snowpack temperature during melt (0 °C). Parameters of wind speed and roughness length, were set to the same values as above for H , and stability was assumed to be neutral.

Model Sensitivity Models for H at the subcanopy site were contrasted with diabatic correction factors for stable and unstable atmospheric conditions (Figure 24). Over 19.5 days, the model utilizing the diabatic correction factor in stable and unstable atmospheric conditions increases energy gains from H by to 33.88 MJ m^{-2} compared to the measured gain of 7.75 MJ m^{-2} . The model used by Boon, 2009 increases energy gain to 24.45 MJ m^{-2} . In this case the added complexity by adding diabatic correction factors for stable and unstable conditions do not produce results closer to that measured (Figure 25), but further modeling efforts to improve predictions of energy gain by H is necessary. Linear relationships between both models and measured data showed poor correlation, with a correlation coefficient ('r value') of the parsimonious model at .2616, and the more complex model with an r value of .2953. Additionally, windspeed estimates were likely lower than values given, which would increase the magnitude of flux.

Tables

Measurement	Sensor	Site Installed
Incoming Shortwave Radiation	NR01 Net Radiometer	S,C*,H**,B
Outgoing Shortwave Radiation	NR01 Net Radiometer	S,C*,H**,B
Incoming Longwave Radiation	NR01 Net Radiometer	S,C*,H**,B
Outgoing Longwave Radiation	NR01 Net Radiometer	S,C*,H**,B
Depth	SR50 Sonic Distance Sensor	S,C,H**,B**
Snow Pack Temperature	Thermocouple wires	H**,B
Snow Surface Temperature	SI-111 Infrared Temp Sensor	S,C
Air Temperature/RH	HMP-50 Temp/RH probe	S,C,H**
Ground Heat Flux	HFP01 Heat Flux Plate	S,C
Sensible Heat Flux	CSAT 3 and LI-7200	S
Latent Heat Flux	CSAT 3 and LI-7200	S

Table 1: Elements measured at each site indicated with sensor description. * clearcut used a CNR1 Net radiometer, ** installed in fall, 2011.

Stand Characteristic	Subcanopy	Infested	Healthy
Average DBH (cm)	26.4	26.6	17.51
Median DBH (cm)	26	28	17.5
Basal Area (m ²)	41.4	80.7	62.9
Stand Height	16.4	19.6	22.2
% Dead	~	53.7	23.9
% Infected	~	39	63.4
% Lodgepole Pine	>96	75.6	63.4
DBH Standard Deviation (cm)	4.85	8.04	7.33
Stems/10m Radius	23	41	71

Table 2: Stand Characteristics at the subcanopy, infested, and healthy sites.

Figures

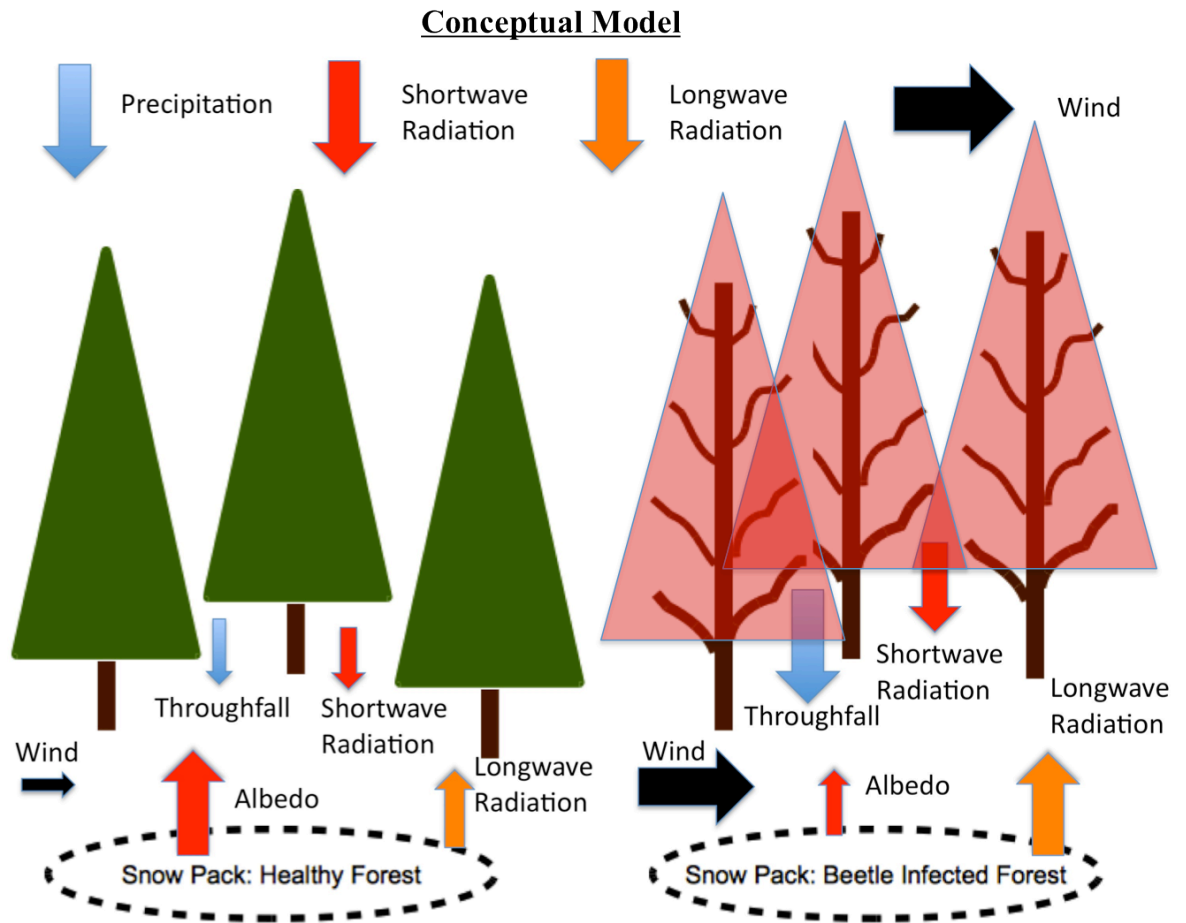


Figure 1: Components that impart a physical influence on snow energy dynamics. A canopy reduced by MPB is likely to experience increased transmission of SW_{in} , while the more open sky is likely to increase LW_{out} . Additionally, throughfall is likely to increase due to the lower stem density for interception.

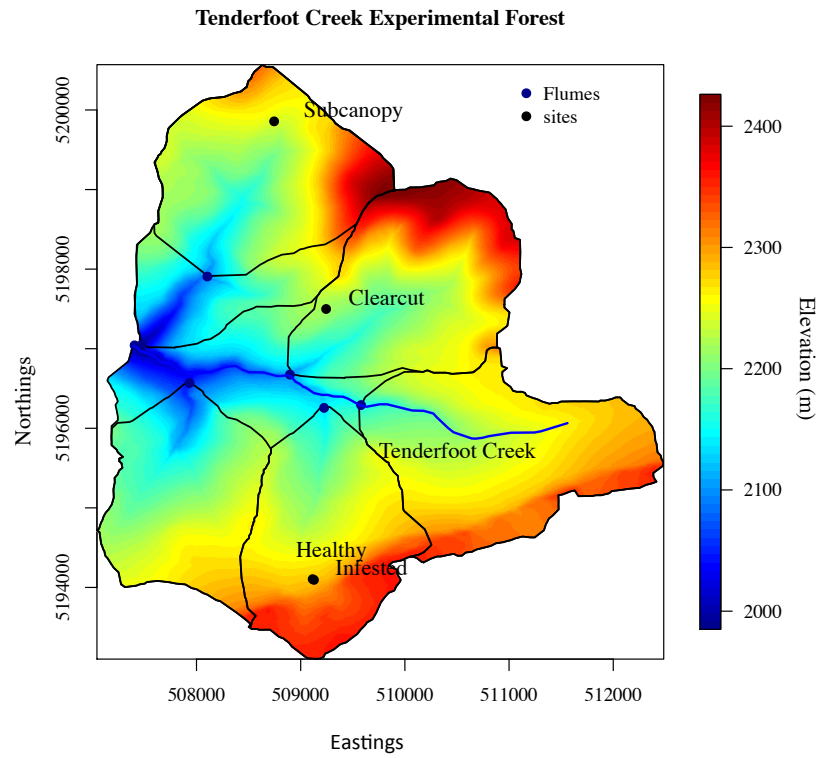
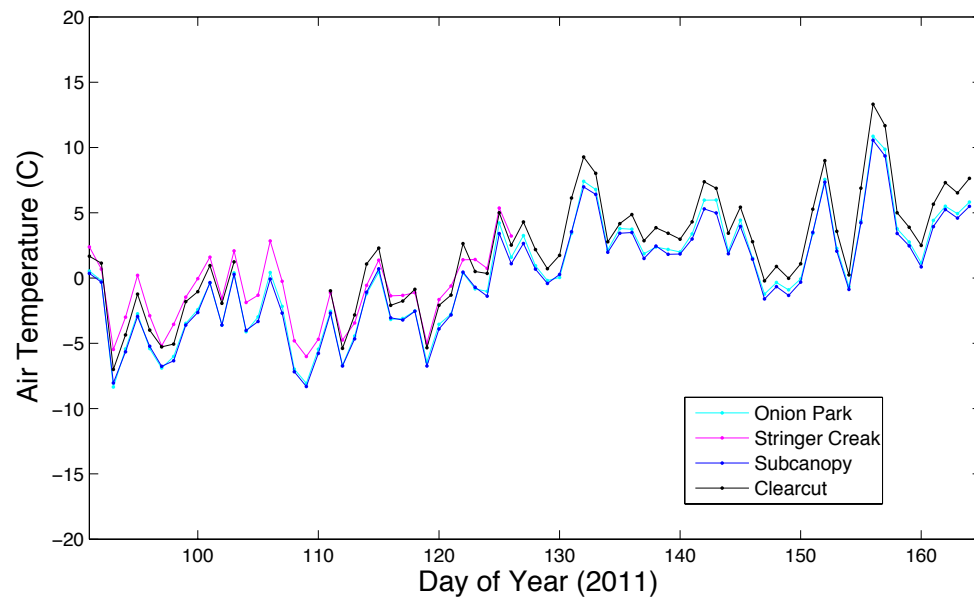


Figure 2: TCEF Elevation map with site and SNOTEL locations. The Healthy and Infested sites are 20m apart for comparisons. The other site locations are on different aspects and elevations, thus provide reference of change over time but not direct comparisons.

A.



B.

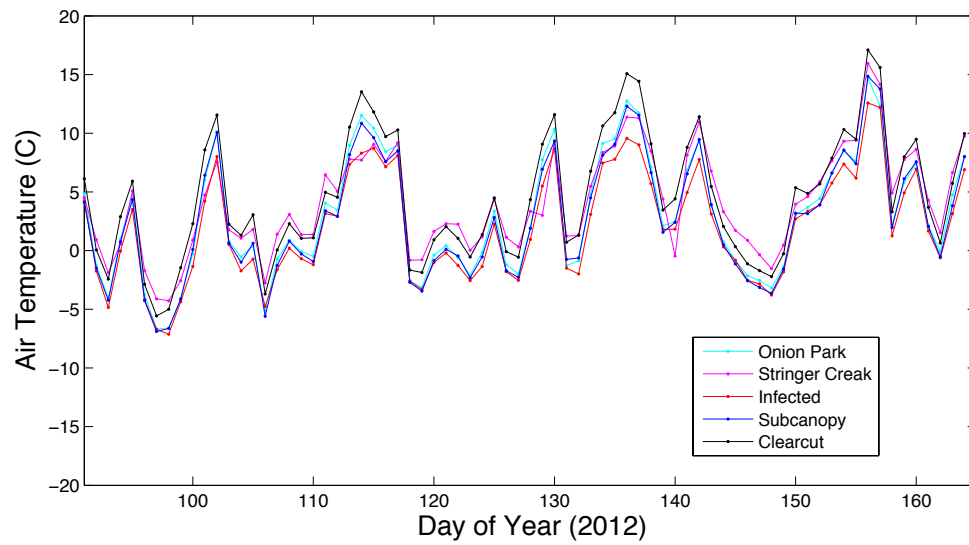


Figure 3: Average daily temperatures for Onion Park, Stringer Creek, subcanopy, and infested sites during the melt periods of 2011 (A) and 2012 (B).

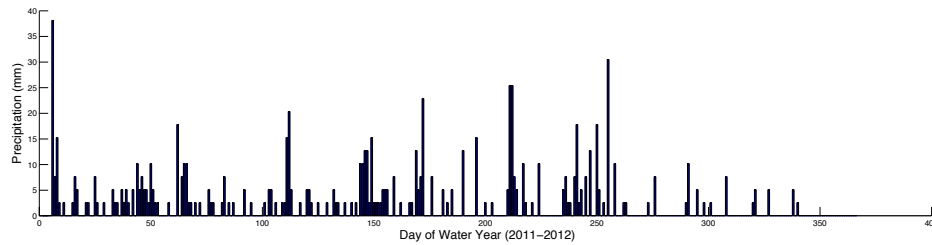
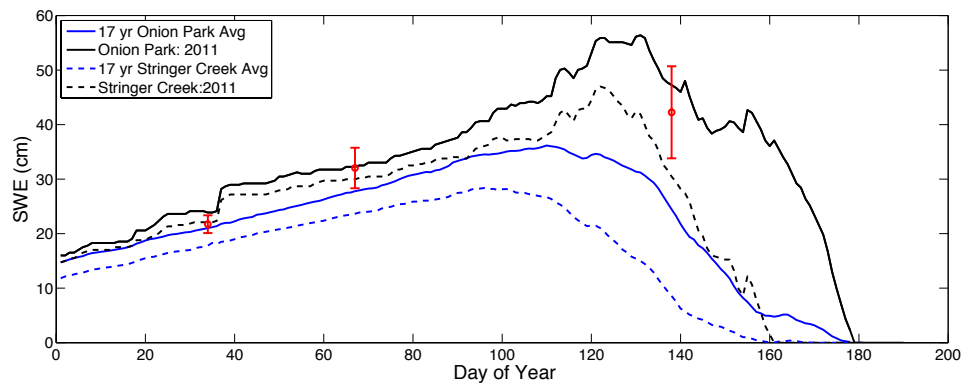


Figure 4: Precipitation (mm) at Onion Park Snotel primarily occurs outside of the summer season, with more frequency during the fall and winter months. However, substantial precipitation events occur in late spring as well.

A



B

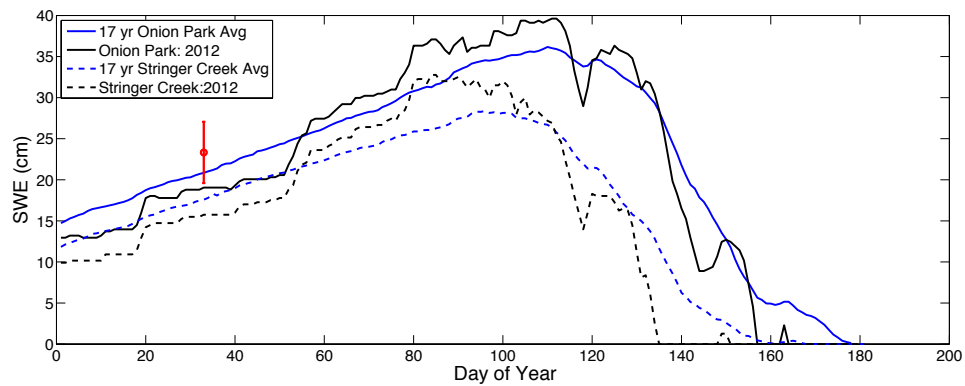


Figure 5 : Snow Water Equivalent from January 1 through June 27 for 2011 (solid black) and 2012 (dashed black) calculated from 1 and 3 hour readings as available for the Onion Park (A) and Stringer Creek (B) SNOTEL sites.

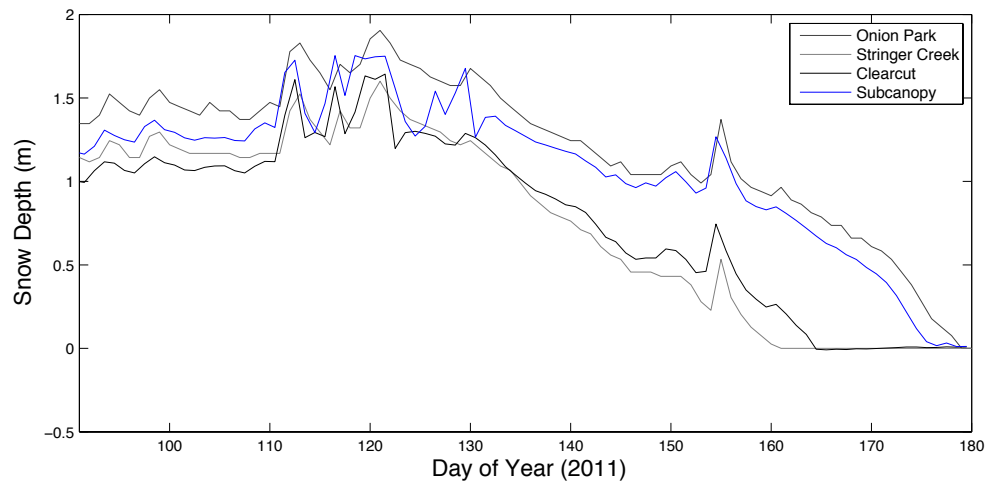
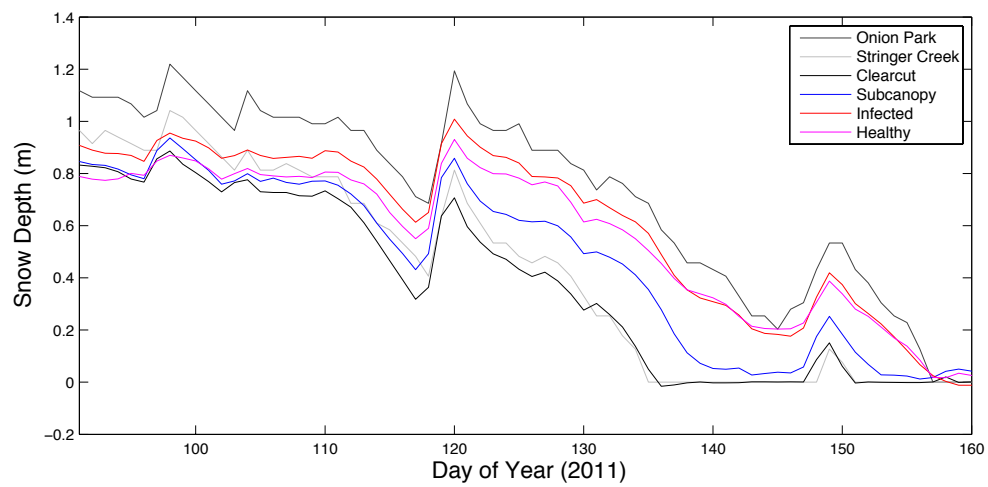
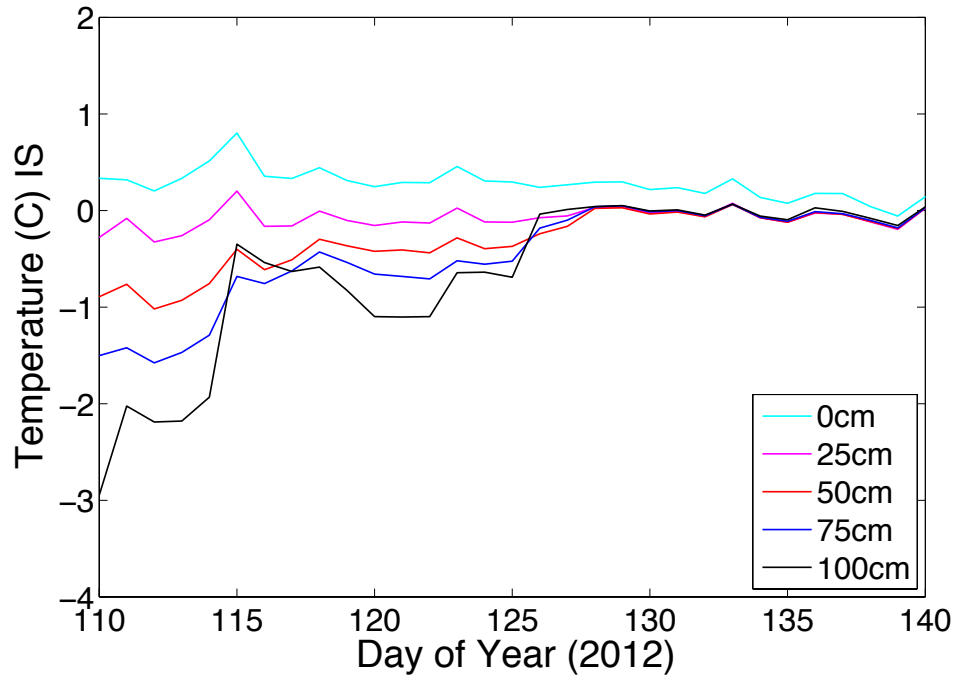
A**B**

Figure 6: Snow depth as recorded at Stringer Creek, Onion Park, subcanopy, infested, healthy, and clearcut sites in (A) 2011 and (B) 2012.

A.



B.

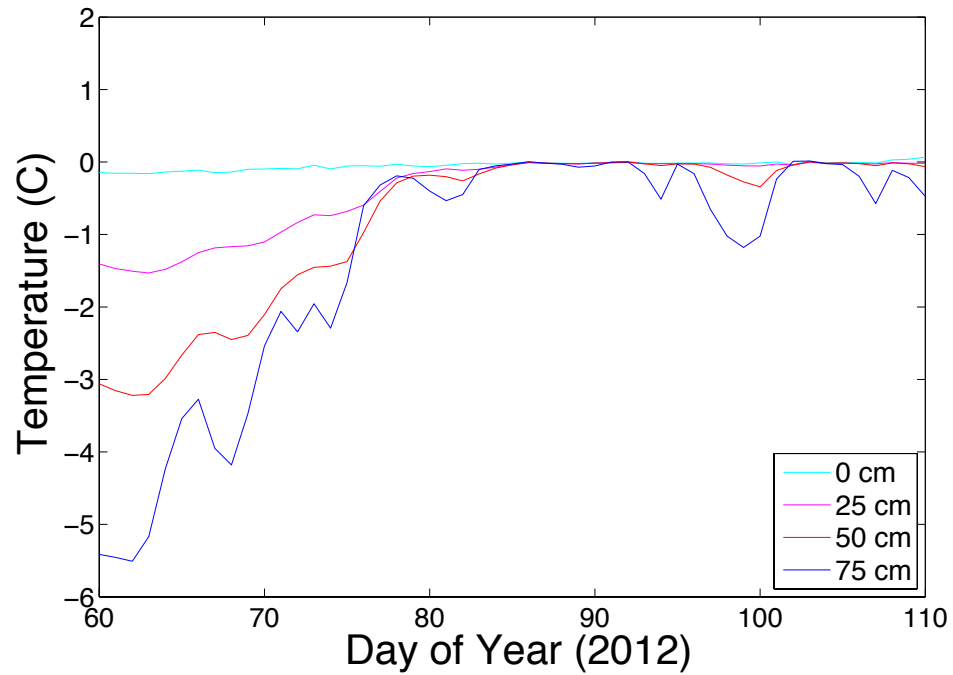


Figure 7: Measured snow temperature at different heights in the snowpack during the melt period of 2012 at the infested site, emphasizing the point around day of year 126 (2011) and 80 (2012) at which the snowpack becomes isothermal.

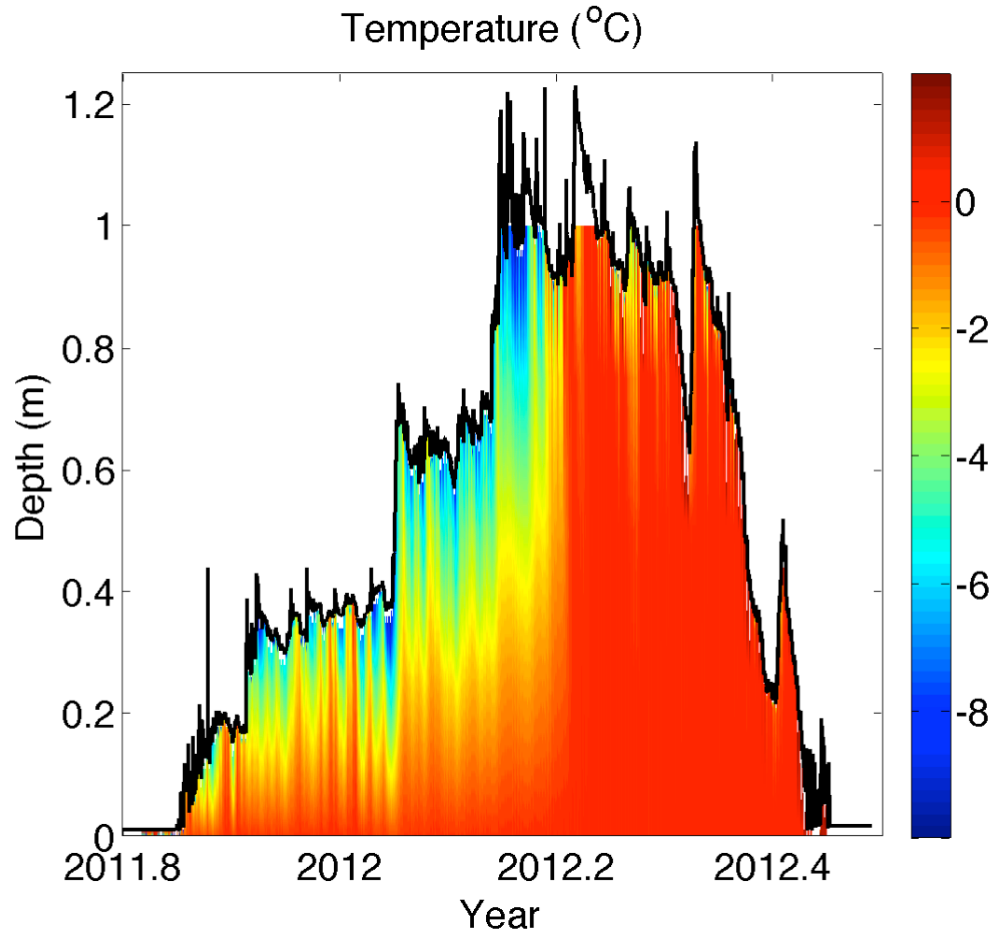


Figure 8: Interpolated snow temperature at the infested site, for the winter of 2011-2012, using observations of air temperature and a snow temperature ladder. The entire snowpack becomes isothermal during the melt period and subsequent rapid melt occurs.

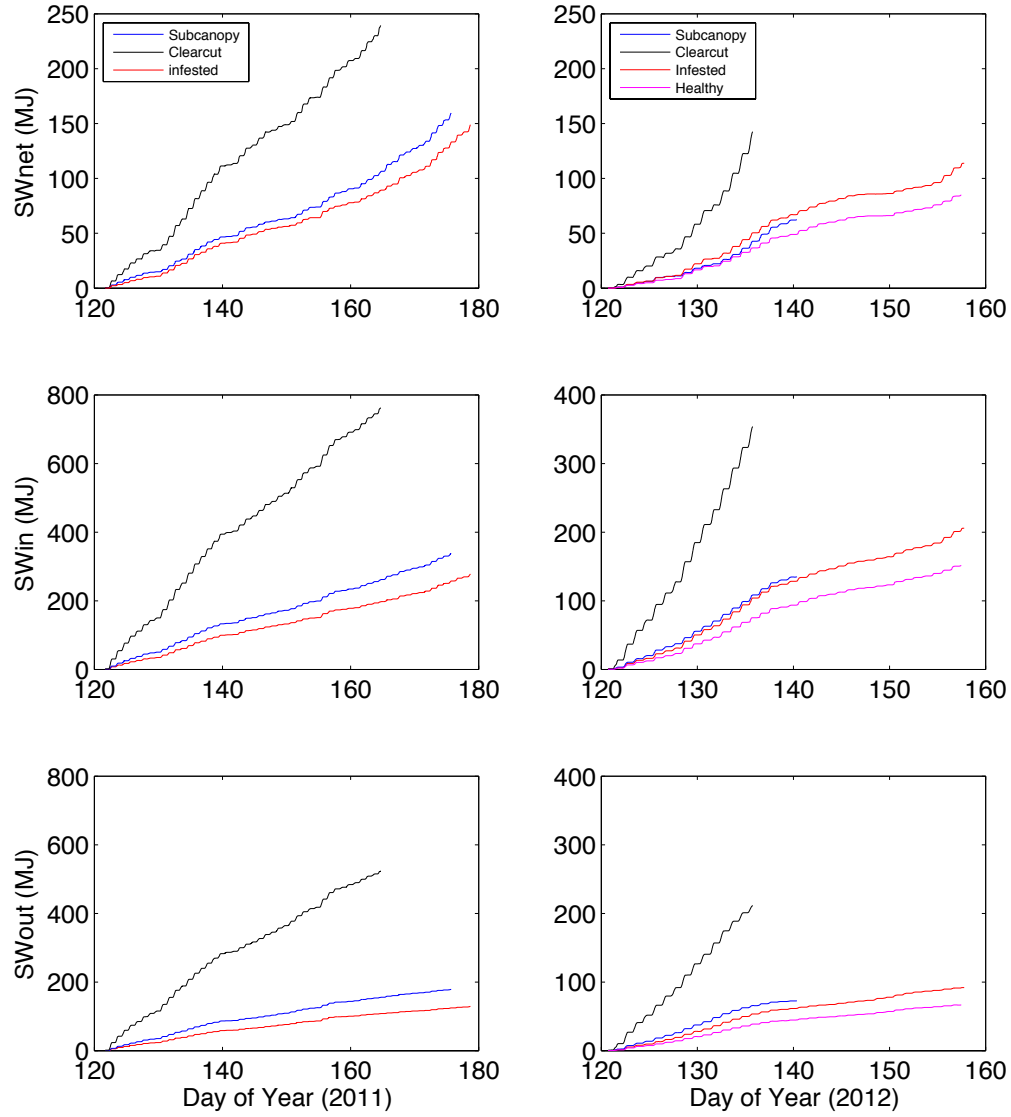
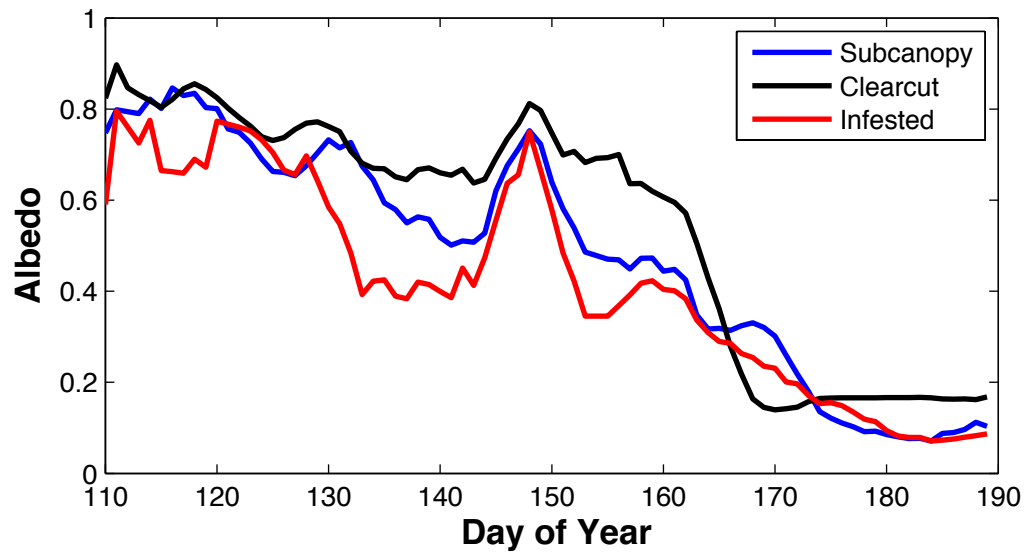


Figure 9: Net (SW_{net}), incident (SW_{in}) and outgoing (SW_{out}) shortwave radiation flux during melt periods of 2011 and 2012 at the TCEF study sites. The clearcut flux density is clearly separated from forested sites. The infested site receives more in 2012 when normalized against the clearcut.

A



B

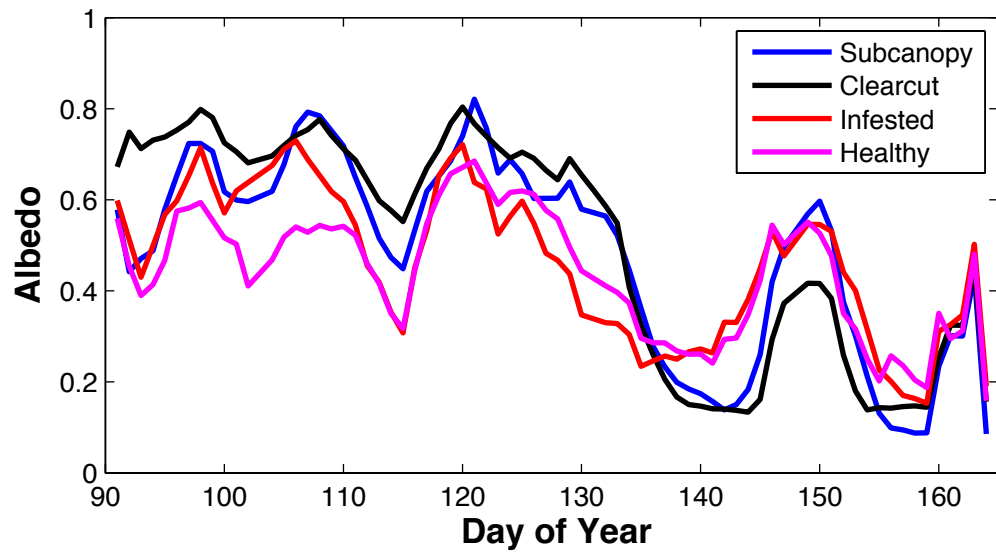


Figure 10: Noontime albedo for the 2011 (A) and 2012 (B) melt season at the study stands in the TCEF experimental forest, using a 10 reading running average for display.

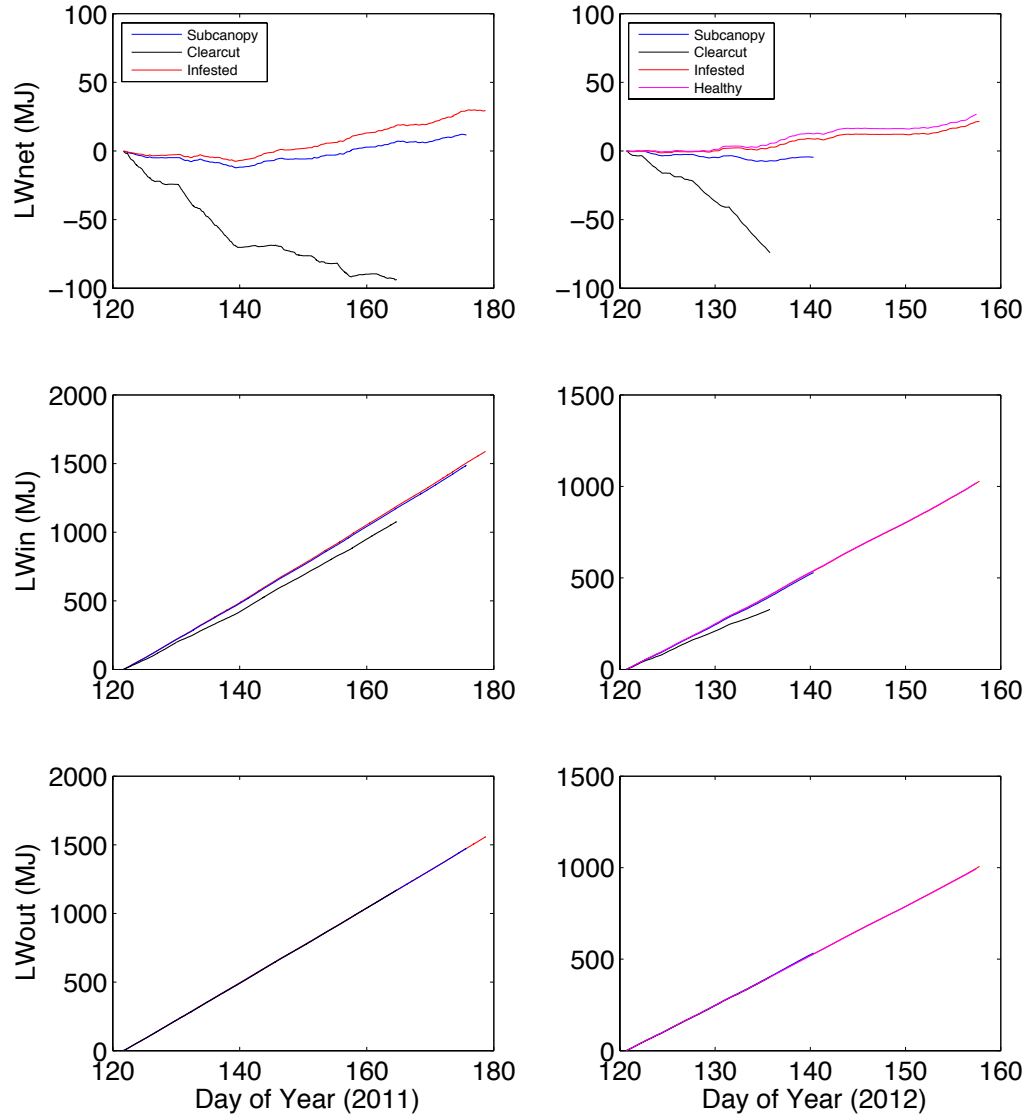


Figure 11: LW radiation for melt periods of 2011 and 2012 for clearcut, subcanopy, infested, and healthy sites. LW_{out} is similar among sites due to the fairly consistent surface temperature of snow. LW_{in} is greater in sites containing canopies, as the trees effectively emit LW after heating from SW_{in} and in acting as a ‘thermal blanket’.

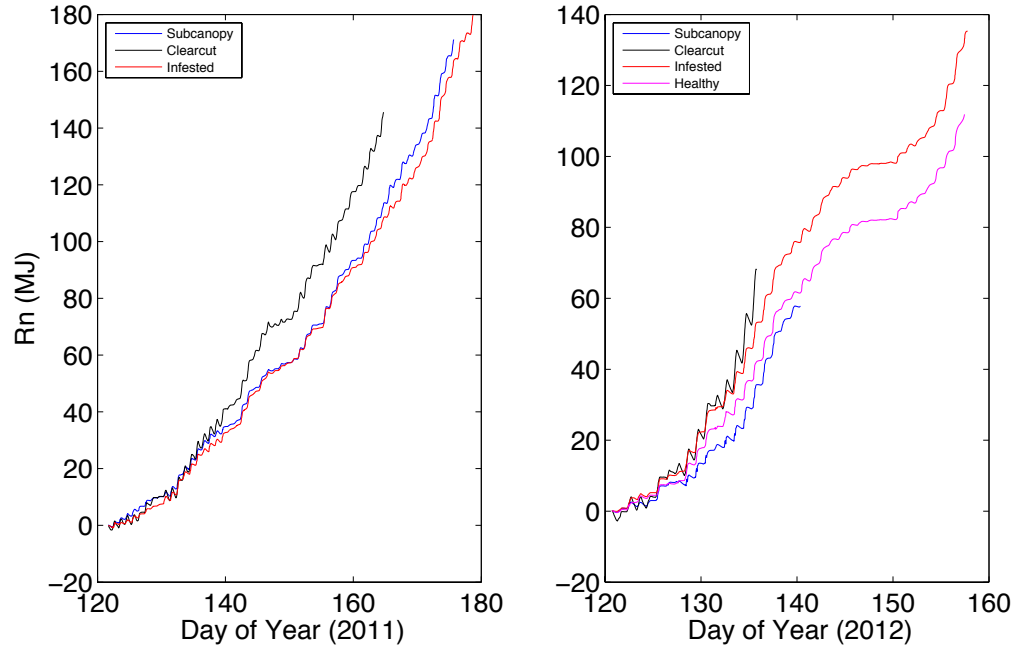


Figure 12: Cumulative available radiation at the snow pack including SW_{net} , SW_{in} , SW_{out} , LW_{net} , LW_{in} , and LW_{out} for the subcanopy, clearcut, and infested in 2011, with the addition of the healthy in 2012. R_n begins to increase dramatically at CC during the latter part of spring, as the longer days combined with a more southerly aspect allow for SW_{in} contribution to increase. Nighttime losses in LW_{out} can be seen as small decreases at the CC, but are even less noticeable at the sites with canopies. The SC snowpack has lower cumulative R_n due to a slightly negative LW_{net} , while SW_{net} is fairly similar to HS and IS.

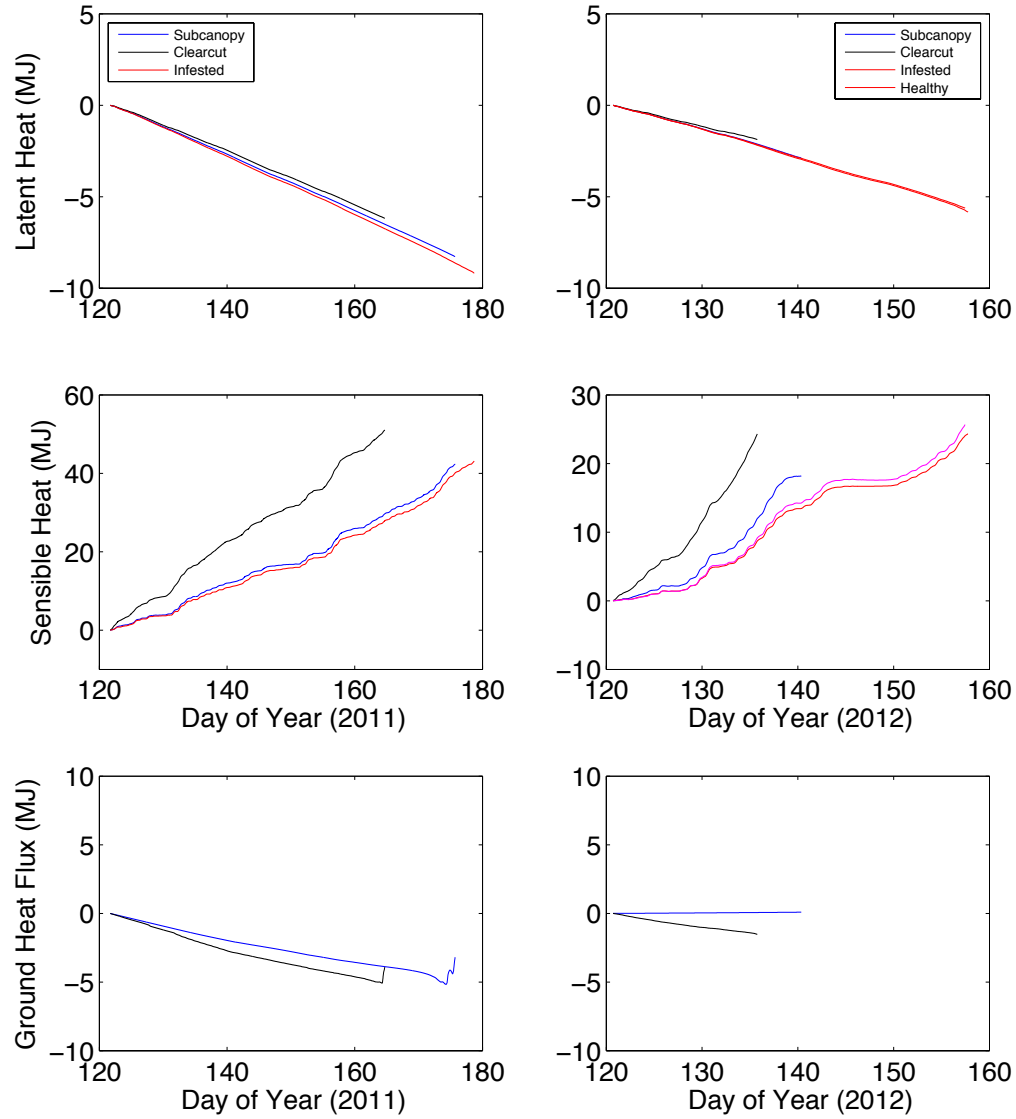


Figure 13: Modeled cumulative H , λE , and measured G flux at the clearcut, subcanopy, infested, sites in 2011, and with the addition of the healthy in 2012. Departure in cumulative λE between the clearcut and other sites does not occur until *ca.* day 173 in 2011, at which point snow depth was logged as 0. 2012 show similar results in lack of significant differences between sites. However, H at the clearcut is noticeably higher than other sites during both years, and increases until complete snowmelt. Cumulative H levels indicate a average flux closer to 0 after snow melt. G is slightly negative when measured at the subcanopy and clearcut sites until complete snow melt.

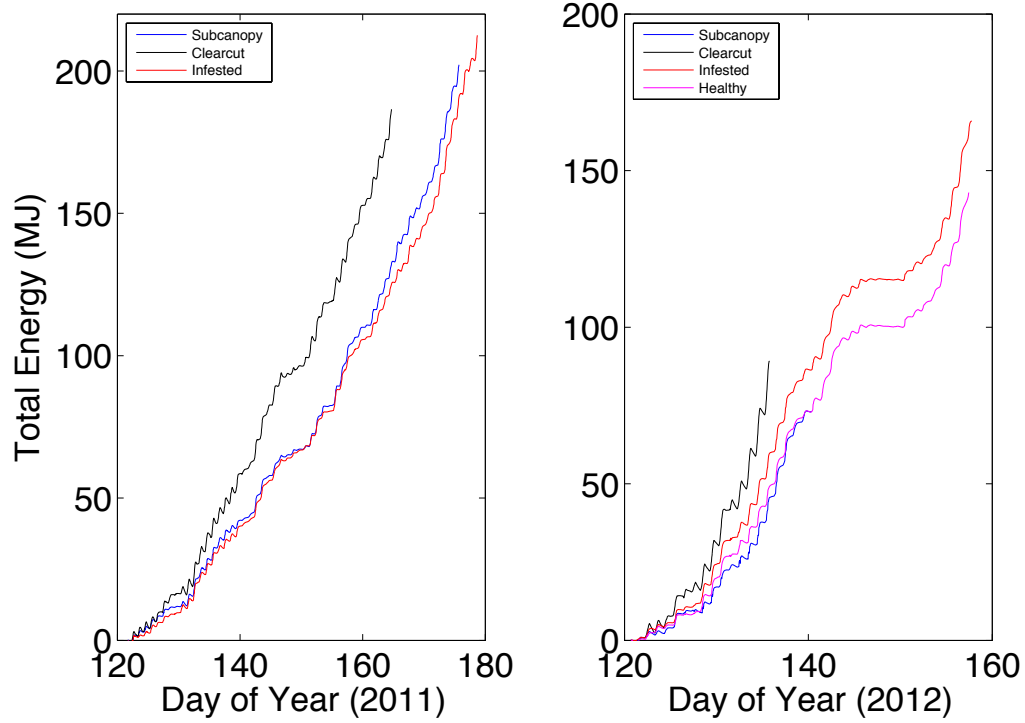


Figure 14: Cumulative energy to snowpacks including R_n , H , λE , and G over the period of observed declining snowpacks for the clearcut, subcanopy and infested sites in 2011, with the addition of the healthy site in 2012. Modeled turbulent fluxes have a positive effect on available energy to melt due to greater H gains than λE losses. However, values are based solely on temperature gradients of snow and overlying air should not be considered accurate.

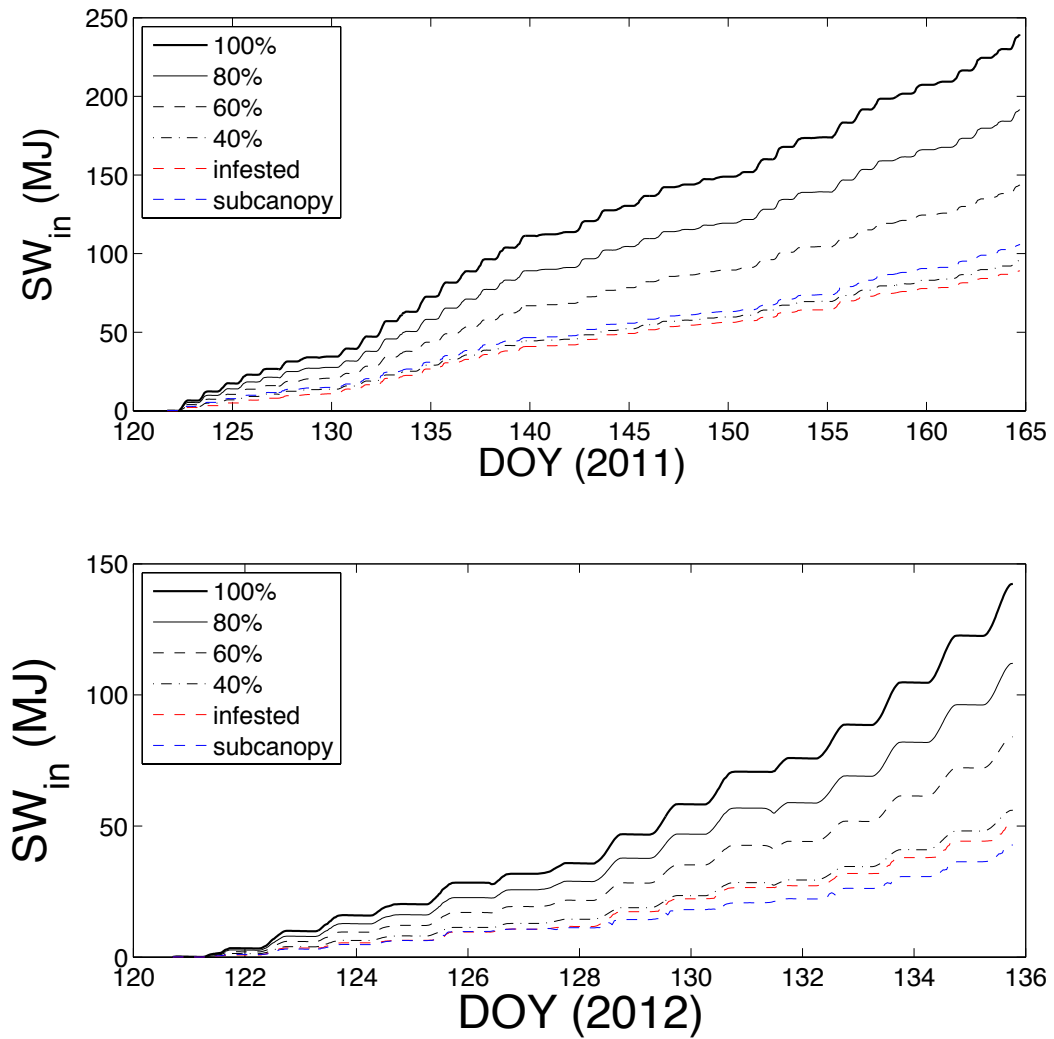


Figure 15: Clearcut SW_{in} under reduction scenarios for 2011 and 2012 with the subcanopy and infested site actual measurements for reference. In 2011, SW_{in} would be reduced to 40% of its original values to achieve similar cumulative totals with the forested sites. In 2012, a reduction to 40% is still slightly higher than forested sites exemplifying the high degree to which a canopy attenuates SW_{in} .

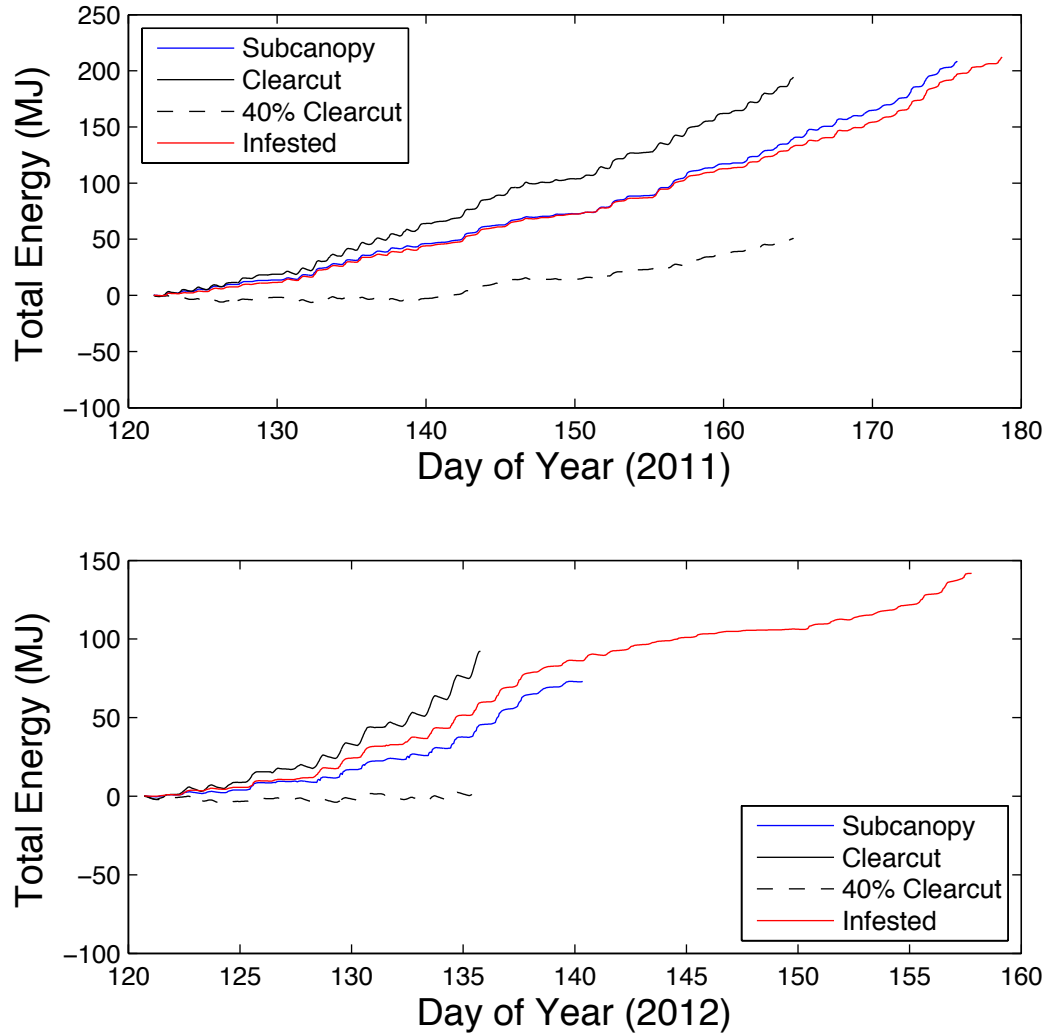


Figure 16: Effects on clearcut Q_m with approximate canopy attenuation on transmission for 2011 and 2012 with subcanopy and infested sites for reference. The clearcut would not melt out (negative Q_m) if SW_{net} was decreased to the level of a forested site. This provides insight to the import role of LW_{net} and turbulent fluxes (H and λE) play in clearcuts. As a canopy degrades, a forest site begins to approach that of clearcuts (Gryning, Batchvarova, & De Bruin, 2001).

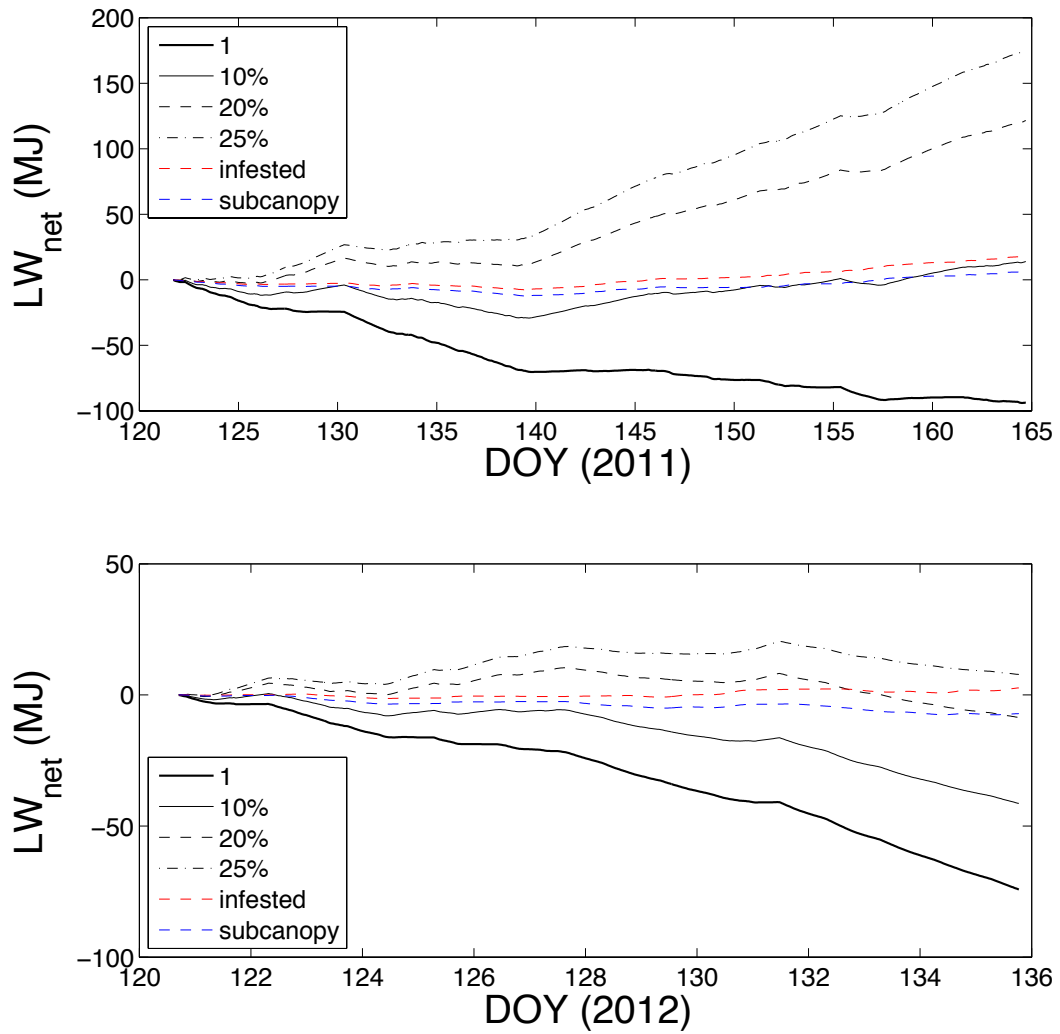


Figure 17: LW_{net} at the clearcut under scenarios of increasing canopy cover for 2011 and 2012 with the subcanopy and infested sites for reference. The canopies of the forested sites effectively emit LW, decreasing losses to LW_{out} by *ca* 10% in 2011 and 20-25% in 2012.

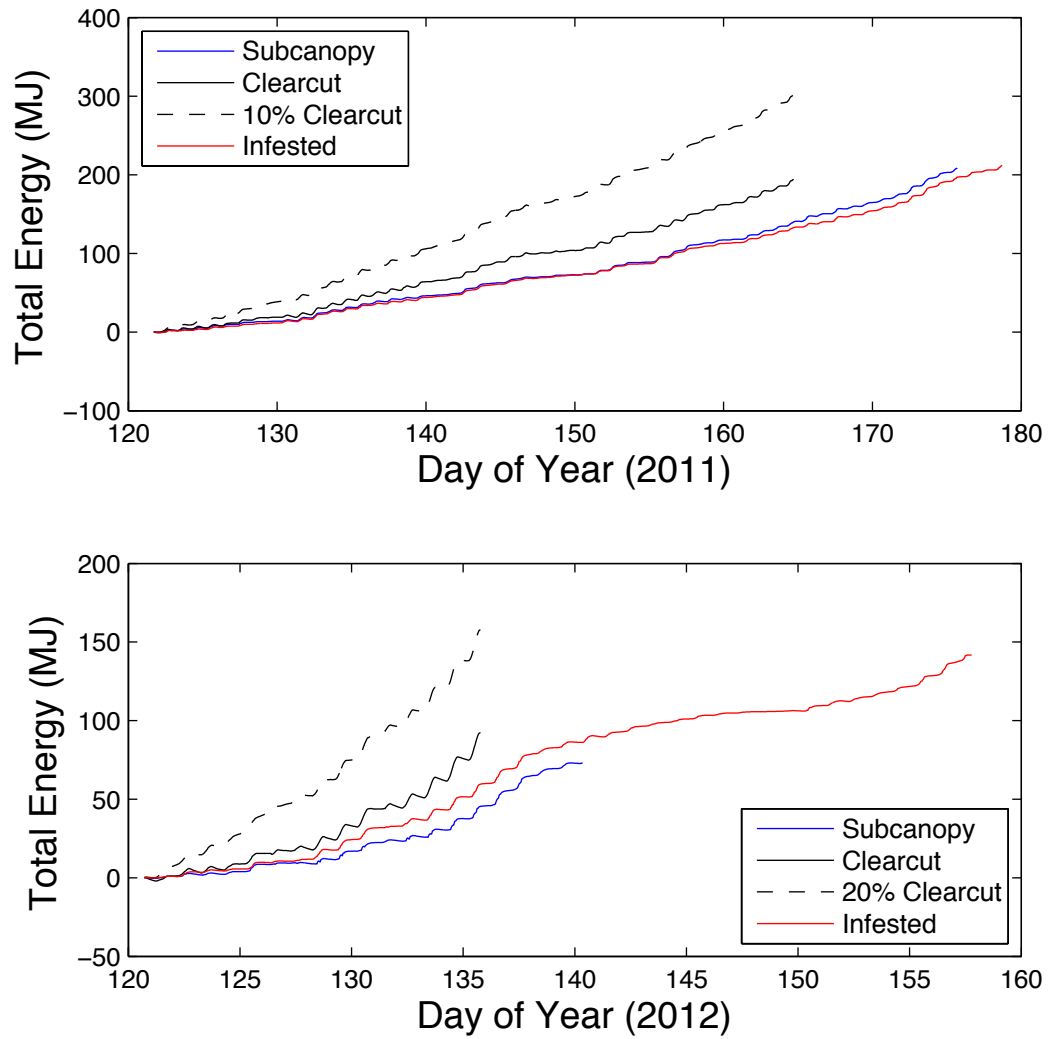


Figure 18: Q_m of the clearcut with LW_{in} increased by 10% in 2011 and 20% in 2012 to mimic that of the forested sites. The losses to LW_{out} are an important piece to attenuating melt rates at the clearcut.

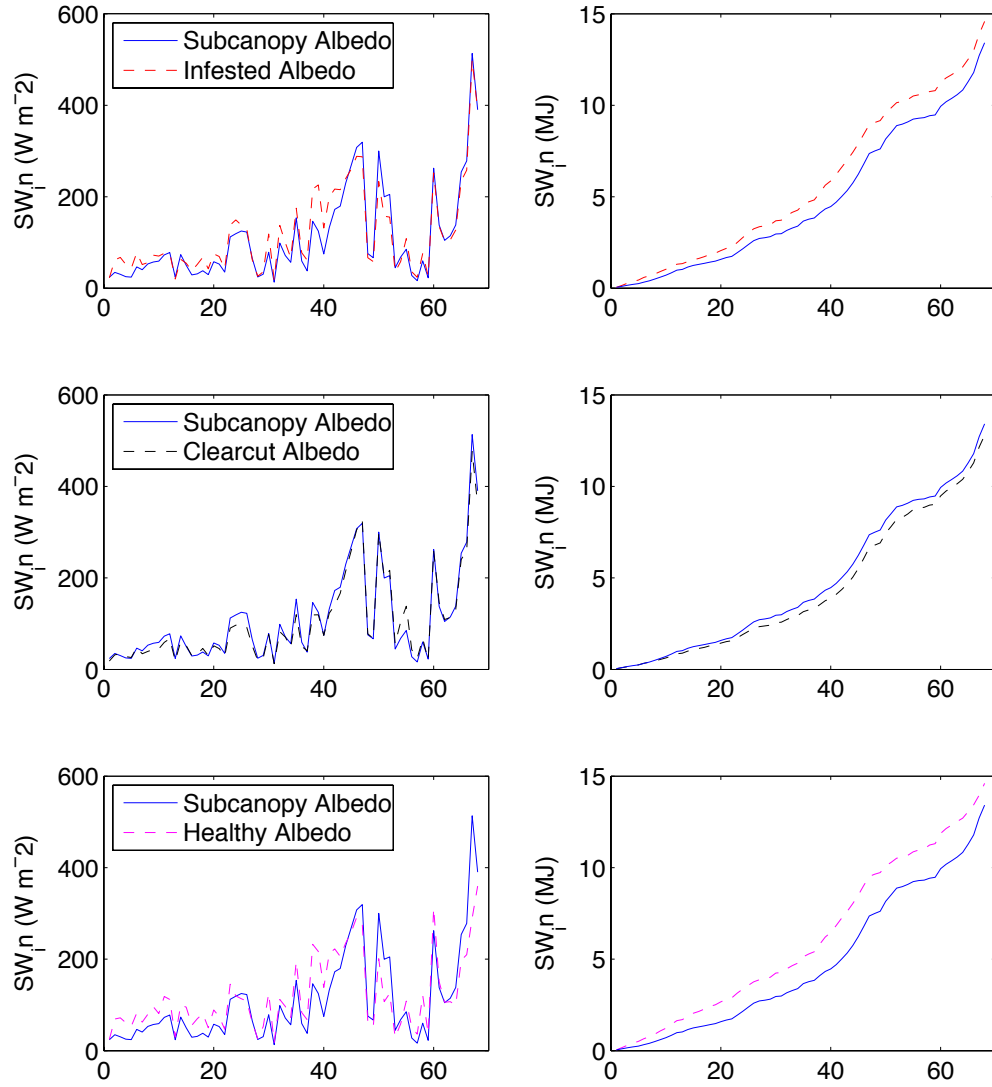


Figure 19: Contributions of SW_{in} of the subcanopy site under scenarios in which albedo from the clearcut, infested, and healthy sites are parameterized. Running averages of noon-time albedos were selected over a period of 67 days and assigned to corresponding noon time SW_{in} data at the subcanopy site, then subtracted from original values to give energy input contributions SW_{in} .

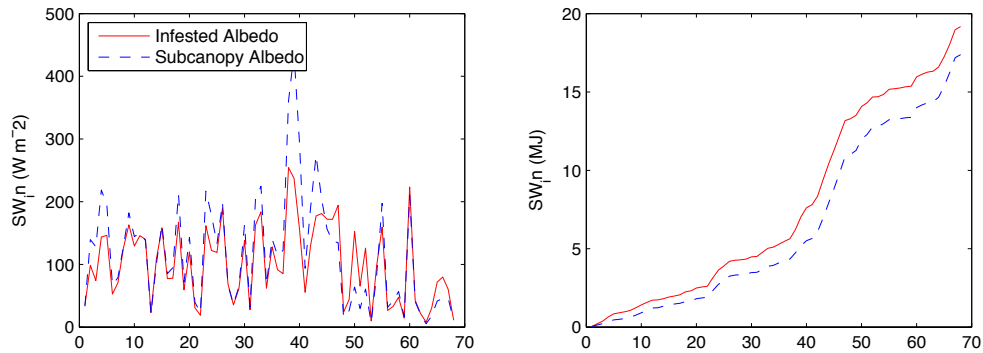


Figure 20: SW_{in} at the infested site with the subcanopy running noontime average albedo parameterized. Inputs of SW_{in} would be attenuated, and with more SW effectively reflected and reradiated away from the snowpack.

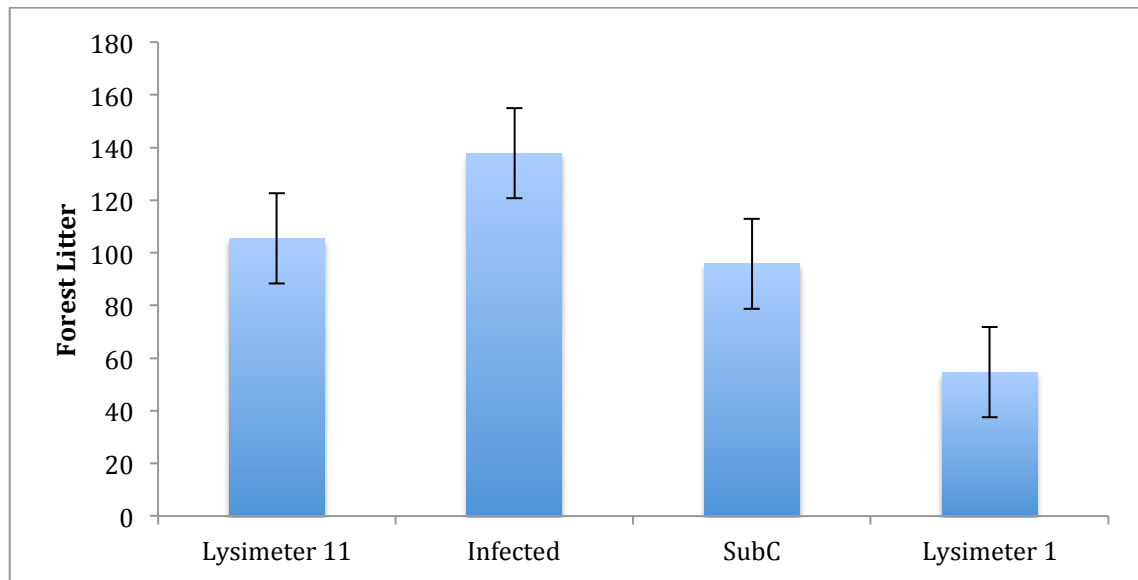


Figure 21: Leaf litter mass collected over winter of 2011-2012. Lysimeter locations were chosen to represent variability across elevations, with lysimeter 1 at *ca.* 2450 meters and lysimeter 11 at *ca.* 2200 meters.

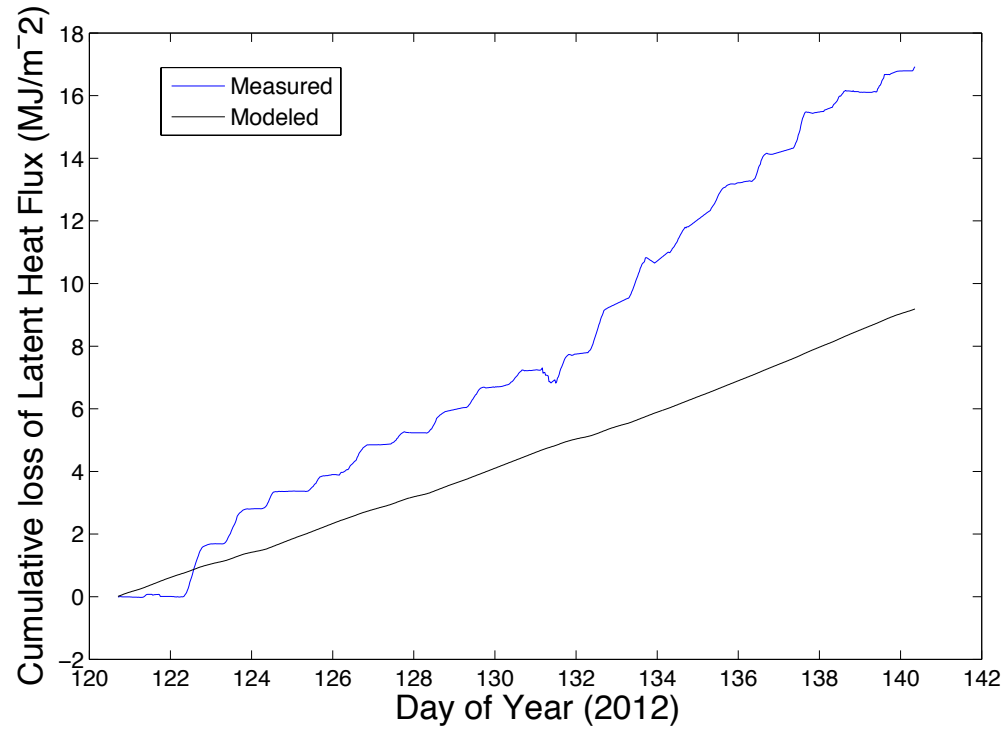


Figure 23: Cumulative totals of measured λE compared to model calculated using the bulk aerodynamic theory. Measured total is 84% higher than modeled, which amounts to a 7.7 MJ/m² over a common melt period of 15 days.

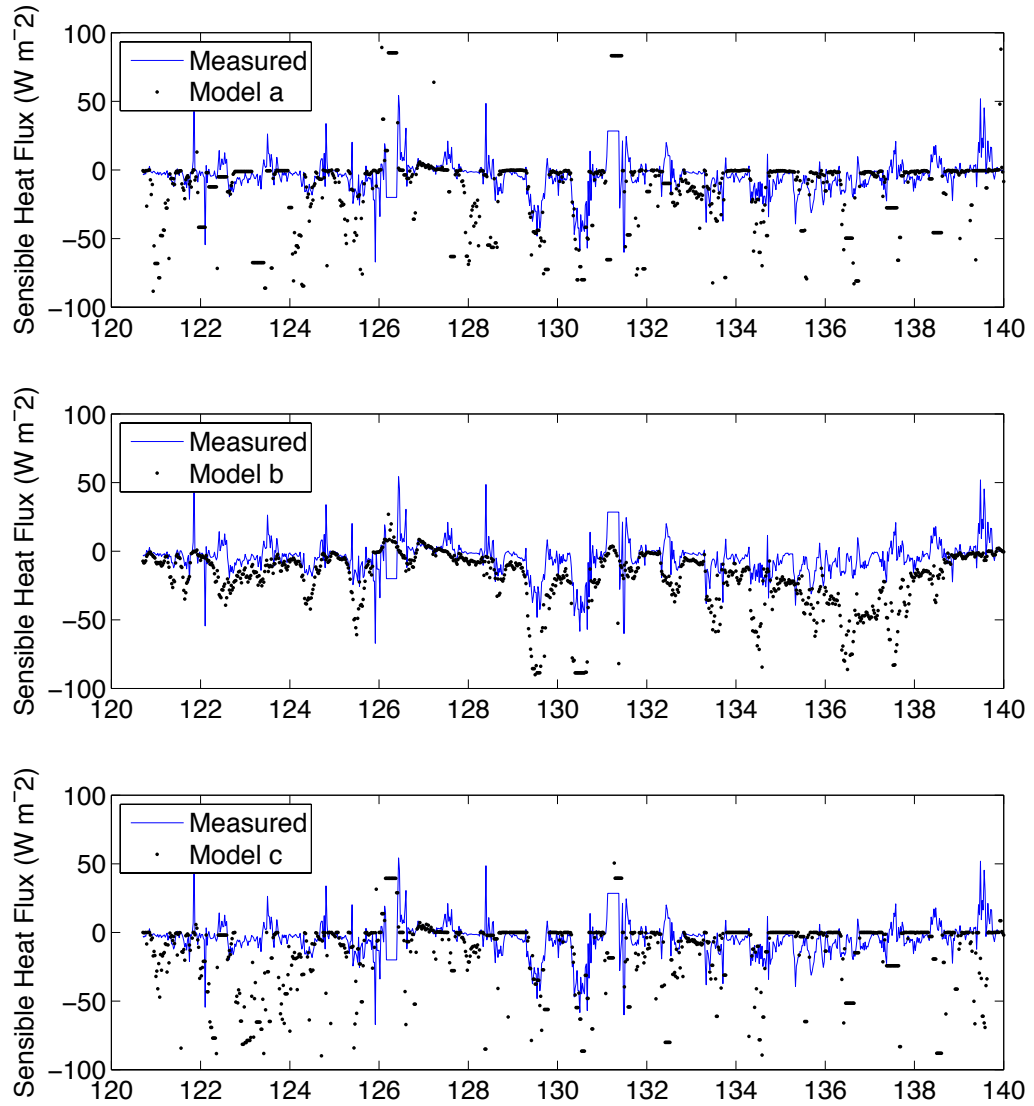


Figure 24: H measured and three models tested: using the bulk aerodynamic theory with the assumptions made for neutral atmospheric conditions such as in Boon (2009) (a), using the same bulk aerodynamic theory, but with diabatic correction factors for stable and unstable conditions, and (c) the bulk aerodynamic theory with the Monin-Obukhov similarity theory to account for stable and unstable atmospheric conditions.

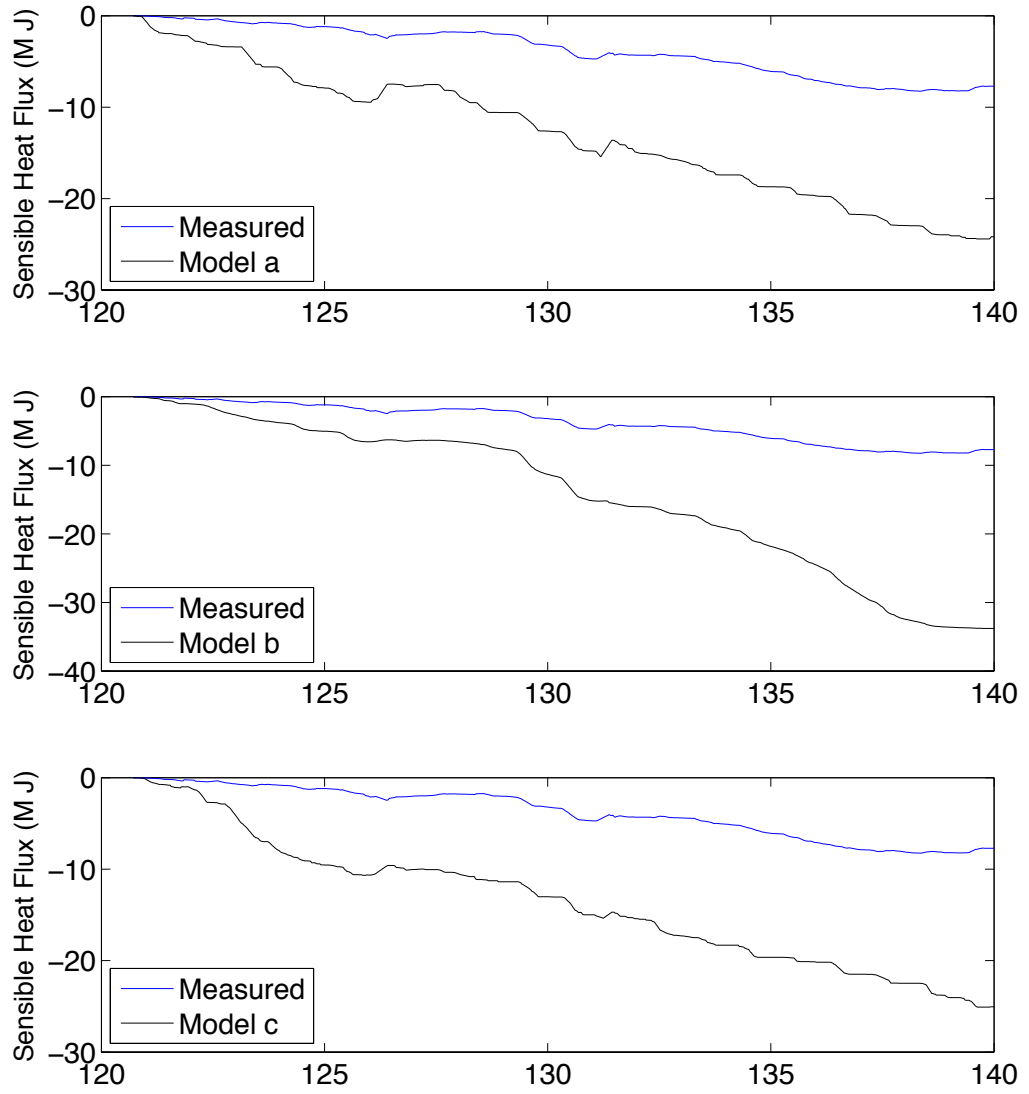


Figure 25: Measured and modeled cumulative H with the bulk aerodynamic theory and neutral atmospheric conditions assumed (a), with diabatic correction factors for stable and unstable atmospheric conditions (b), and using the Monin-Obukhov similarity theory to account for stable and unstable atmospheric conditions.

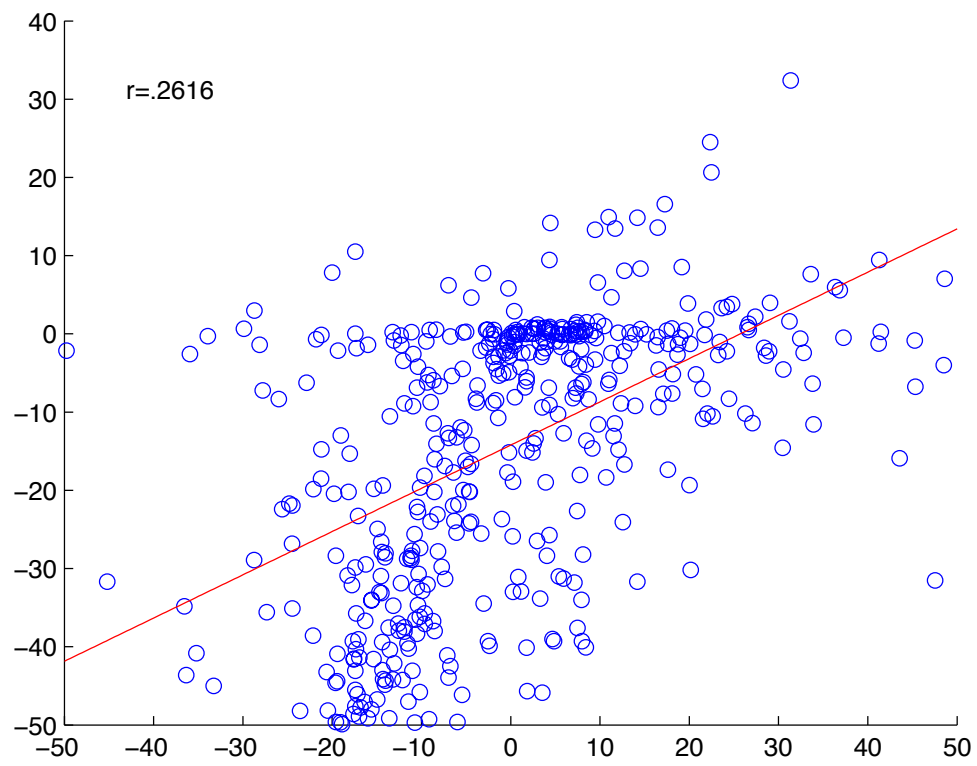


Figure 26: Scatter plot of measured and modeled H assuming neutral atmospheric stability.



Figure 27: Scatter plot of measured and modeled H with a diabatic correction factor for unstable and stable atmospheric conditions.

REFERENCES

- Aguado, E. (1985). Radiation Balances of Melting Snow Covers at an Open Site in the Central Sierra Nevada, California. *Water Resources Research*, 21(11), 1649–1654.
- Aukema, B. H., Carroll, A. L., Zheng, Y., Zhu, J., Raffa, K. F., Dan Moore, R., Stahl, K., et al. (2008). Movement of outbreak populations of mountain pine beetle: influences of spatiotemporal patterns and climate. *Ecography*, 31(December 2007), 348–358. doi:10.1111/j.2007.0906-7590.05453.x
- Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066), 303–9. doi:10.1038/nature04141
- Boon, S. (2009). Snow ablation energy balance in a dead forest stand. *Hydrologic Processes*, 23(January), 2600–2610. doi:10.1002/hyp
- Cayan, D. R. (1996). Interannual Climate Variability and Snowpack in the Western United States. *Journal of Climate*, 9(5), 928–948.
- Dominguez, F., Rivera, E., Lettenmaier, D. P., & Castro, C. L. (2012). Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models. *Geophysical Research Letters*, 39(5), 1–7. doi:10.1029/2011GL050762
- Emanuel, R. E., Epstein, H. E., McGlynn, B. L., Welsch, D. L., Muth, D. J., & D’Odorico, P. (2010). Spatial and temporal controls on watershed ecohydrology in the northern Rocky Mountains. *Water Resources Research*, 46(11), 1–14. doi:10.1029/2009WR008890
- Emanuel, R. E., Riveros-Iregui, D. a., McGlynn, B. L., & Epstein, H. E. (2011). On the spatial heterogeneity of net ecosystem productivity in complex landscapes. *Ecosphere*, 2(7), art86. doi:10.1890/ES11-00074.1
- Essery, R., Pomeroy, J., Ellis, C., & Link, T. (2008). Modelling longwave radiation to snow beneath forest canopies using hemispherical photography or linear regression, *Hydrological Processes*, 22(June), 2788–2800. doi:10.1002/hyp
- Farnes, P. E., Shearer, R. C., McCaughey, W. W., & Hanson, K. J. (1995). Comparisons of Hydrology, geology, and Physical Characteristics between Tenderfoot Creek Experimental Forest (East Side) Montana, and Coram Experimental Forest (West Side) Montana (pp. 1–20).

- Gryning, S.-E., Batchvarova, E., & De Bruin, H. A. R. (2001). Energy balance of a sparse coniferous high-latitude forest under winter conditions. *Boundary-Layer Meteorology*, 99, 465–488.
- Hardy, J. P., Davis, R. E., Jordan, R., Li, X., Woodcock, C., & Ni, W. (1997). Snow ablation modeling at the stand scale in a boreal jack pine forest, 102(96), 397–405.
- Hardy, J. P., Melloh, R., Robinson, P., & Jordan, R. (2000). Incorporating effects of forest litter in a snow process model. *Hydrological Processes*, 3237(September), 3227–3237.
- Harestad, A. S., & Bunnell, F. L. (1981). Prediction of snow-water equivalents in coniferous forests. *Canadian Journal of Forest Research*, 11(4), 854-857.
- Jencso, K. G., & McGlynn, B. L. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research*, 47(11), 1–16. doi:10.1029/2011WR010666
- Jessie, E., Carroll, A. L., & Taylor, S. W. (2003). Effect of climate change on range expansion by the mountain pine beetle in British Columbia.
- Kinsey, M., Stoy, P., Johnson, A., Kaiser, K., Rains, A., Moore, W., McGlynn, B., (2011). Digital Photography for detecting change in Lodgepole Pine Forests. Poster session presented at the
- Kaiser, K. E., McGlynn, B. L., & Emanuel, R. E. (2012). Ecohydrology of an outbreak: mountain pine beetle impacts trees in drier landscape positions first. *Ecohydrology*, n/a–n/a. doi:10.1002/eco.1286
- Kurz, W. a, Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, a L., Ebata, T., et al. (2008). Mountain pine beetle and forest carbon feedback to climate change. *Nature*, 452(April), 987–90. doi:10.1038/nature06777
- Kustas, W.P., Rango, A., and Uijlenhoet, R. (1994) A simple energy budget algorithm for the snowmelt runoff model. *Water Resources Research*, 30(5), 1515-27
- Lee, X., Finnigan, J., & Paw U, K. (2005). Coordinate systems and flux bias error. *Handbook of Micrometeorology*, 33–66.
- Maidment D. 1993. *Handbook of Hydrology*, 1424. McGraw Hill Professional: New York.

- Marks, D., & Davis, E. (1992). Climate and Energy Exchange at the Snow Surface in the Alpine Region of the Sierra Nevada Measurements and Monitoring. *Water Resources Research*, 28(11), 3029–3042.
- Marks, D., & Dozier, J. (1992). Climate and Energy Exchange at the Snow Surface in the Alpine Region of the Sierra Nevada 2 . Snow Cover Energy Balance. *Water Resources Research*, 28(11), 3043–3054.
- Marks, D., & Winstral, A. (2001). Comparison of Snow Deposition , the Snow Cover Energy Balance , and Snowmelt at Two Sites in a Semiarid Mountain Basin. *Journal of Hydrometeorology*, 2(3), 213–227.
- Mauder, M., & Foken, T. (2004). Documentation and instruction manual of the eddy covariance software package TK2 (Vol. 26). Univ., Abt. Mikrometeorologie.
- Mincemoyer, S. A., & Birdsall, J. L. (2006). Vascular flora of the Tenderfoot Creek Experimental Forest, Little Belt Mountains, Montana. *Madrono* 53(3), 211–222. doi:10.3120/0024-9637(2006)53
- Mitton, J. B., & Ferrenberg, S. M. (2012). Mountain pine beetle develops an unprecedented summer generation in response to climate warming. *The American naturalist*, 179(5), 163–71. doi:10.1086/665007
- Molotch N. P., (2009) Reconstructing snow water equivalent in the Rio Grande headwaters using remotely sensed snow cover data and a spatially distributed snowmelt model. *Hydrological Processes* 23:7, 1076-1089
- Moncrieff, J. B., Massheder, J. M., De Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., et al. (1997). A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. *Journal of Hydrology*, 188, 589–611.
- Moncrieff, J., Clement, R., Finnigan, J., & Meyers, T. (2005). Averaging, detrending, and filtering of eddy covariance time series. In X. Lee, W. Massman, & B. E. Law (Eds.), *Handbook of Micrometeorology* (pp. 7–31). Springer.
- Moore, R. D. 1983. On the use of bulk aerodynamic formulae over melting snow. *Nordic Hydrol.*, 14(4), 193-206
- Nippgen, F., McGlynn, B. L., Marshall, L. a., & Emanuel, R. E. (2011). Landscape structure and climate influences on hydrologic response. *Water Resources Research*, 47(12), 1–17. doi:10.1029/2011WR011161
- Pacific, V. J., Jencso, K. G., & McGlynn, B. L. (2010). Variable flushing mechanisms and landscape structure control stream DOC export during snowmelt in a set of

- nested catchments. *Biogeochemistry*, 99(1-3), 193–211. doi:10.1007/s10533-009-9401-1
- Pacific, V. J., McGlynn, B. L., Riveros-Iregui, D. a., Welsch, D. L., & Epstein, H. E. (2011). Landscape structure, groundwater dynamics, and soil water content influence soil respiration across riparian-hillslope transitions in the Tenderfoot Creek Experimental Forest, Montana. *Hydrological Processes*, 25(5), 811–827. doi:10.1002/hyp.7870
- Palmer, P. L. (1988). The SCS snow survey water supply forecasting program: Current operations and future directions. *Proc. Western Snow Conf.*, Kalispell,, 43 –51.
- Pomeroy, J. W., Marks, D., Link, T., Ellis, C., Hardy, J., Rowlands, A., & Granger, R. (2009). The impact of coniferous forest temperature on incoming longwave radiation to melting snow, 2525(May), 2513–2525. doi:10.1002/hyp
- Pomeroy, J. W., Gray, D. M., Hedstrom, N. R., & Janowicz, J. R. (2002). Prediction of seasonal snow accumulation in cold climate forests. *Hydrological Processes*, 16(18), 3543–3558. doi:10.1002/hyp.1228
- Potts, D. (1984). Hydrologic impacts of a large-scale mountain pine beetle Epidemic. *Water Resources Bulletin*, 20(3), 373–377.
- Pugh, E., & Small, E. (2012). The impact of pine beetle infestation on snow accumulation and melt in the headwaters of the Colorado River. *Ecohydrology*, 5(4), 467–477. doi:10.1002/eco.239
- Raffa, K. F., Aukema, B. H., Bentz, B. J., Carroll, A. L., Hicke, J. a., Turner, M. G., & Romme, W. H. (2008). Cross-scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. *BioScience*, 58(6), 501-517. doi:10.1641/B580607
- Riveros-Iregui, D. a., & McGlynn, B. L. (2009). Landscape structure control on soil CO₂ efflux variability in complex terrain: Scaling from point observations to watershed scale fluxes. *Journal of Geophysical Research*, 114(G2), 1–14. doi:10.1029/2008JG000885
- Riveros-Iregui, D. a., McGlynn, B. L., Emanuel, R. E., & Epstein, H. E. (2012). Complex terrain leads to bidirectional responses of soil respiration to inter-annual water availability. *Global Change Biology*, 18(2), 749–756. doi:10.1111/j.1365-2486.2011.02556.x
- Riveros-Iregui, D. a., McGlynn, B. L., Marshall, L. a., Welsch, D. L., Emanuel, R. E., & Epstein, H. E. (2011). A watershed-scale assessment of a process soil CO₂

- production and efflux model. *Water Resources Research*, 47, 1–12.
doi:10.1029/2010WR009941
- Safranyik, L., Carroll, A. L., & Wilson, B. (2007). The biology and epidemiology of the mountain pine beetle in lodgepole pine forests. *The mountain pine beetle: a synthesis of biology, management and impacts on lodgepole pine*, 3-66.
- Samman, S. and Logan, J. (2000). Assessment and response to bark beetle outbreaks in the Rocky Mountain area. Report to Congress from Forest Health Protection, Washington Office, Forest Service, USDA. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-62, 46 pp
- United States Army Corps of Engineers. 1956. Snow Hydrology: Summary Report of the Snow Investigations, US Army Corps of Engineers, North Pacific Division: Portland, OR.
- Varhola, A., Coops, N. C., Weiler, M., & Moore, R. D. (2010). Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*, 392(3-4), 219–233. doi:10.1016/j.jhydrol.2010.08.009
- Warren, S. G., & Wiscombe, W. J. (1980). A Model for the Spectral Albedo of Snow. II: Snow Containing Atmospheric Aerosols. *Journal of the Atmospheric Sciences*, 37, 2734–2745.
- Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase western US forest wildfire activity. *Science*, 313(5789), 940-943.
- Winkler, R., Boon, S., Zimonick, B., & Baleshta, K. (2010). Assessing the effects of post-pine beetle forest litter on snow albedo. *Hydrological Processes*, 24(6), 803–812. doi:10.1002/hyp.7648
- Woods, S. W., Ahl, R., Sappington, J., & McCaughey, W. (2006). Snow accumulation in thinned lodgepole pine stands, Montana, USA. *Forest Ecology and Management*, 235(1-3), 202–211. doi:10.1016/j.foreco.2006.08.013

CHAPTER 3

SUMMARY / CONCLUSIONS

Meteorological measurements and modeled results of each component in the snow energy balance were made at a clearcut, subcanopy, infested, and healthy site. Measurements were taken over winters of 2011 and 2012, with 2011 being an abnormally high snow year, and 2012 being relatively average. These results suggest that:

- 1) Canopy attenuation of SW_{in} transmission to the snow pack greatly reduces the input of SW radiation to the snow energy budget as a whole. A MPB infested stand in the red stage shows evidence of change in canopy structure over time, essentially allowing more SW_{in} . However, a red stand has held enough needles and branches such that SW contributions to the snowpack are still closer to that of a forested site.
- 2) Albedos at forested stands are generally lower than at clearcuts, until just before complete melt out. Increased needle fall in a MPB stand decreases albedo, but a stand with a higher basal area and heterogeneity can have equally or even lower albedo. The combination of lowering albedo and increased SW_{in} consequentially has positive effects on R_n .
- 3) LW_{in} is enhanced by a canopy, which effectively acts as a thermal blanket. The cooler open sky over a clearcut snowpack has reduced inputs of LW_{in} . Higher canopy density and basal areas have a positive effect on LW_{in} . In the case of forests impacted by MPB, one would expect LW_{in} to fall as the canopy diminishes

and approaches the openness of a clearcut. However, this study did not observe these expected changes in LW_{in} in a MPB stand, suggesting a longer time scale to which alterations in LW_{in} to occur.

- 4) Measured turbulent fluxes of H and λE account for less than 24% of total energy for melt at the subcanopy site, suggesting R_n is the major driver of snowmelt in forested canopies. However, turbulent flux also establishes itself as a non-trivial component to SNOBAL. Future eddy flux measurements within a MPB infested stand would further our understanding of changes in turbulent flux that accompany dying stands.
- 5) Ground heat flux plays a small role in snow melt until the snow is optically thin and patchy enough for the soil to receive atmospheric inputs of energy, and measured values at the subcanopy and clearcut sites are less than the commonly assumed sub-snow values of 3.13 W m^{-2} .
- 6) Our measurements suggest that the current models using the bulk aerodynamic theory greatly underestimates turbulent flux in forests, and that careful measurements of wind, air pressure, surface temperature, and air temperature, must be obtained and used with close parameterizations of surface roughness lengths in order to accurately balance the energy budget.
- 7) Modeled H is not significantly improved with stability correction factors, and in this case, often produced results further from measured values.

Post-epidemic MPB infected watersheds have seen advanced hydrographs and increased water yields (Potts, 1984), but the mechanisms that relate the MPB damaged canopies to snow accumulation and ablation, remain poorly understood. Studies on the impacts of MPB disturbance on snow have focused on continuous measurements at a grey stand, healthy stand, and clearcut (Boon, 2009), or on intermittent measurements across pairs of healthy and red-stage plots (Pugh & Small, 2012). At this point, no studies have continuously measured the energy balance of snow in healthy, clearcut, and red-stage stands. Available eddy-covariance instrumentation allowed for further investigation into turbulent exchanges of sensible and latent heat flux between the snow and atmosphere, across melt periods of two characteristically different years.

My research emphasizes that forest canopy characteristics alter meteorological conditions of underlying snowpacks when they undergo change themselves. Variability in annual precipitation, temperature, and cloudiness can either accentuate or reduce the magnitude of these alterations.

Snowpack was deeper at the infested site than the adjacent healthy site, suggesting the infested stand had less canopy interception of snow, and therefore less sublimation from the canopy to the atmosphere.

Results suggest that MPB infested stands during the red stage are just beginning to undergo snow altering defoliation. An observable increase in the transmission of SW_{in} at the infested site relative to the subcanopy site occurred over 2011 to 2012. In addition, albedo was observed to be lower at the infested site, with greater biomass falling to the snowpack, and decreasing the snows reflective properties of SW .

Snowpack was deeper at the infested site than the adjacent healthy site, suggesting the infested stand had less canopy interception of snow, and therefore less sublimation from the canopy to the atmosphere.

LW_{in} varied little between forested sites, suggesting that a stand in the red stage continues to act like a healthy stand in the emission of LW radiation toward the snowpack. However, as needles fall and the canopy becomes less dense, LW inputs are expected to progressively trend more towards what was observed at the clearcut, in which LW_{in} drops considerably, and consequentially effecting Q_m .

Turbulent fluxes of H and λE were measured at the subcanopy site, and modeled under the bulk aerodynamic theory. Measured flux was underestimated by the models on both accounts. In the case of H , diabatic correction factors for stable and unstable conditions were added, but were found to deviate further from measured data than the more parsimonious model. Future efforts in comparing models with measured turbulent flux under a variety of canopy regimes will provide a better understanding toward how a MPB altered stand will change H and λE .

This investigation highlights the importance of R_n for snow melt, and provides insight on turbulent flux under forested canopies, effectively allowing new research in the field to ask more defined questions.

REFERENCES

- Aguado, E. (1985). Radiation Balances of Melting Snow Covers at an Open Site in the Central Sierra Nevada , California. *Water Resources Research*, 21(11), 1649–1654.
- Amman, G. D. (1977). The role of the mountain pine beetle in lodgepole pine ecosystems: impact on succession. In *The role of arthropods in forest ecosystems* (pp. 3-18). Springer Berlin Heidelberg.
- Aoki, T. (2003). Effects of snow physical parameters on shortwave broadband albedos. *Journal of Geophysical Research*, 108(D19), 1–12. doi:10.1029/2003JD003506
- Aukema, B. H., Carroll, A. L., Zheng, Y., Zhu, J., Raffa, K. F., Dan Moore, R., Stahl, K., et al. (2008). Movement of outbreak populations of mountain pine beetle: influences of spatiotemporal patterns and climate. *Ecography*, 31(December 2007), 348–358. doi:10.1111/j.2007.0906-7590.05453.x
- Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066), 303–9. doi:10.1038/nature04141
- Bewley, D., Alila, Y., & Varhola, A. (2010). Variability of snow water equivalent and snow energetics across a large catchment subject to Mountain Pine Beetle infestation and rapid salvage logging. *Journal of Hydrology*, 388, 464–479. doi:10.1016/j.jhydrol.2010.05.031
- Boon, S. (2009). Snow ablation energy balance in a dead forest stand. *Hydrologic Processes*, 23(January), 2600–2610. doi:10.1002/hyp
- Cayan, D. R. (1996). Interannual Climate Variability and Snowpack in the Western United States. *Journal of Climate*, 9(5), 928–948.
- Cole, W. E., & Amman, G. D. (1969). Mountain pine beetle infestations in relation to lodgepole pine diameters (Vol. 95). US Dept. of Agriculture, Forest Service, Intermountain Forest & Range Experiment Station.
- Denitto, G., Egan, J., Lockman, B., Sontag, S., Brytten, S., Sturdevant, N., & Gannon, A. (2011). *Montana Forest Insect and Disease Conditions and Program Highlights - 2011*.

- DeWalle, D. R. (School of F. R. at the P. S. U., & Rango, A. (USDA A. R. S. (2008). *Principles of Snow Hydrology* (p. 165). Cambridge University Press.
- Dominguez, F., Rivera, E., Lettenmaier, D. P., & Castro, C. L. (2012). Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models. *Geophysical Research Letters*, 39(5), 1–7. doi:10.1029/2011GL050762
- Ellis, C. R., & Pomeroy, J. W. (2007). Estimating sub-canopy shortwave irradiance to melting snow on forested slopes, 21, 2581–2593. doi:10.1002/hyp
- Emanuel, R. E., Epstein, H. E., McGlynn, B. L., Welsch, D. L., Muth, D. J., & D’Odorico, P. (2010). Spatial and temporal controls on watershed ecohydrology in the northern Rocky Mountains. *Water Resources Research*, 46(11), 1–14. doi:10.1029/2009WR008890
- Emanuel, R. E., Riveros-Iregui, D. a., McGlynn, B. L., & Epstein, H. E. (2011). On the spatial heterogeneity of net ecosystem productivity in complex landscapes. *Ecosphere*, 2(7), art86. doi:10.1890/ES11-00074.1
- Essery, R., Pomeroy, J., Ellis, C., & Link, T. (2008). Modelling longwave radiation to snow beneath forest canopies using hemispherical photography or linear regression, *Hydrological Processes*, 22(June), 2788–2800. doi:10.1002/hyp
- Farnes, P. E., Shearer, R. C., McCaughey, W. W., & Hanson, K. J. (1995). Comparisons of Hydrology, geology, and Physical Characteristics between Tenderfoot Creek Experimental Forest (East Side) Montana, and Coram Experimental Forest (West Side) Montana (pp. 1–20).
- Gryning, S.-E., Batchvarova, E., & De Bruin, H. A. R. (2001). Energy balance of a sparse coniferous high-latitude forest under winter conditions. *Boundary-Layer Meteorology*, 99, 465–488.
- Hardy, J. P., Davis, R. E., Jordan, R., Li, X., Woodcock, C., & Ni, W. (1997). Snow ablation modeling at the stand scale in a boreal jack pine forest, 102(96), 397–405.
- Hardy, J. P., Melloh, R., Robinson, P., & Jordan, R. (2000). Incorporating effects of forest litter in a snow process model. *Hydrological Processes*, 3237(September), 3227–3237.
- Harestad, A. S., & Bunnell, F. L. (1981). Prediction of snow-water equivalents in coniferous forests. *Canadian Journal of Forest Research*, 11(4), 854–857.

- Jencso, K. G., & McGlynn, B. L. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research*, 47(11), 1–16. doi:10.1029/2011WR010666
- Jessie, E., Carroll, A. L., & Taylor, S. W. (2003). Effect of climate change on range expansion by the mountain pine beetle in British Columbia.
- Kinsey, M., Stoy, P., Johnson, A., Kaiser, K., Rains, A., Moore, W., McGlynn, B., (2011). Digital Photography for detecting change in Lodgepole Pine Forests. Poster session presented at the
- Kaiser, K. E., McGlynn, B. L., & Emanuel, R. E. (2012). Ecohydrology of an outbreak: mountain pine beetle impacts trees in drier landscape positions first. *Ecohydrology*, n/a–n/a. doi:10.1002/eco.1286
- Kustas, W.P., Rango, A., and Uijlenhoet, R. (1994) A simple energy budget algorithm for the snowmelt runoff model. *Water Resources Research*, 30(5), 1515-27
- Kurz, W. a, Dymond, C. C., Stinson, G., Rampley, G. J., Neilson, E. T., Carroll, a L., Ebata, T., et al. (2008). Mountain pine beetle and forest carbon feedback to climate change. *Nature*, 452(April), 987–90. doi:10.1038/nature06777
- Kustas, W.P., Rango, A., and Uijlenhoet, R. (1994) A simple energy budget algorithm for the snowmelt runoff model. *Water Resources Research*, 30(5), 1515-27
- Lee, X., Finnigan, J., & Paw U, K. (2005). Coordinate systems and flux bias error. *Handbook of Micrometeorology*, 33–66.
- Link, T. E., & Marks, D. (1999). Point simulation of seasonal snow cover dynamics beneath boreal forest canopies *ESC-30, 104*, 841–857.
- Logan, J. A., & Powell, J. A. (2001). Ghost Forests, Global Warming, and the Mountain Pine Beetle (Coleoptera : Scolytidae). *American Entomologist*, 47(3), 160–173.
- Maidment D. 1993. *Handbook of Hydrology*, 1424. McGraw Hill Professional: New York.
- Marks, D., & Davis, E. (1992). Climate and Energy Exchange at the Snow Surface in the Alpine Region of the Sierra Nevada Measurements and Monitoring. *Water Resources Research*, 28(11), 3029–3042.
- Marks, D., & Dozier, J. (1992). Climate and Energy Exchange at the Snow Surface in the Alpine Region of the Sierra Nevada 2 . Snow Cover Energy Balance. *Water Resources Research*, 28(11), 3043–3054.

- Marks, D., & Winstral, A. (2001). Comparison of Snow Deposition , the Snow Cover Energy Balance , and Snowmelt at Two Sites in a Semiarid Mountain Basin. *Journal of Hydrometeorology*, 2(3), 213–227.
- Mauder, M., & Foken, T. (2004). Documentation and instruction manual of the eddy covariance software package TK2 (Vol. 26). Univ., Abt. Mikrometeorologie.
- Mincemoyer, S. A., & Birdsall, J. L. (2006). Vascular flora of the Tenderfoot Creek Experimental Forest, Little Belt Mountains, Montana. *Madrono* 53(3), 211–222. doi:10.3120/0024-9637(2006)53
- Mitton, J. B., & Ferrenberg, S. M. (2012). Mountain pine beetle develops an unprecedented summer generation in response to climate warming. *The American naturalist*, 179(5), 163–71. doi:10.1086/665007
- Molotch N. P., (2009) Reconstructing snow water equivalent in the Rio Grande headwaters using remotely sensed snow cover data and a spatially distributed snowmelt model. *Hydrological Processes* 23:7, 1076-1089
- Moncrieff, J. B., Massheder, J. M., De Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., et al. (1997). A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. *Journal of Hydrology*, 188, 589–611.
- Moncrieff, J., Clement, R., Finnigan, J., & Meyers, T. (2005). Averaging, detrending, and filtering of eddy covariance time series. In X. Lee, W. Massman, & B. E. Law (Eds.), *Handbook of Micrometeorology* (pp. 7–31). Springer.
- Moore, R. D. 1983. On the use of bulk aerodynamic formulae over melting snow. *Nordic Hydrol.*, 14(4), 193-206
- Nault, B., & Eastlund, R. (2006). *Snow Survey & Water Supply Forecasting Program* (pp. 1–4).
- Nippgen, F., McGlynn, B. L., Marshall, L. a., & Emanuel, R. E. (2011). Landscape structure and climate influences on hydrologic response. *Water Resources Research*, 47(12), 1–17. doi:10.1029/2011WR011161
- Pacific, V. J., Jencso, K. G., & McGlynn, B. L. (2010). Variable flushing mechanisms and landscape structure control stream DOC export during snowmelt in a set of nested catchments. *Biogeochemistry*, 99(1-3), 193–211. doi:10.1007/s10533-009-9401-1

- Pacific, V. J., McGlynn, B. L., Riveros-Iregui, D. a., Welsch, D. L., & Epstein, H. E. (2011). Landscape structure, groundwater dynamics, and soil water content influence soil respiration across riparian-hillslope transitions in the Tenderfoot Creek Experimental Forest, Montana. *Hydrological Processes*, 25(5), 811–827. doi:10.1002/hyp.7870
- Palmer, P. L. (1988). The SCS snow survey water supply forecasting program: Current operations and future directions. *Proc. Western Snow Conf., Kalispell,*, 43 –51.
- Pomeroy, J. W., Marks, D., Link, T., Ellis, C., Hardy, J., Rowlands, A., & Granger, R. (2009). The impact of coniferous forest temperature on incoming longwave radiation to melting snow, 2525(May), 2513–2525. doi:10.1002/hyp
- Pomeroy, J. W., Gray, D. M., Hedstrom, N. R., & Janowicz, J. R. (2002). Prediction of seasonal snow accumulation in cold climate forests. *Hydrological Processes*, 16(18), 3543–3558. doi:10.1002/hyp.1228
- Pomeroy, J. W., Gray, D. M., Hedstrom, N. R., & Janowicz, J. R. (2002). Prediction of seasonal snow accumulation in cold climate forests. *Hydrological Processes*, 16(18), 3543–3558. doi:10.1002/hyp.1228
- Potts, D. (1984). Hydrologic impacts of a large-scale mountain pine beetle Epidemic. *Water Resources Bulletin*, 20(3), 373–377.
- Pugh, E., & Small, E. (2012). The impact of pine beetle infestation on snow accumulation and melt in the headwaters of the Colorado River. *Ecohydrology*, 5(4), 467–477. doi:10.1002/eco.239
- Raffa, K. F., Aukema, B. H., Bentz, B. J., Carroll, A. L., Hicke, J. a., Turner, M. G., & Romme, W. H. (2008). Cross-scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. *BioScience*, 58(6), 501-517. doi:10.1641/B580607
- Riveros-Iregui, D. a., & McGlynn, B. L. (2009). Landscape structure control on soil CO₂ efflux variability in complex terrain: Scaling from point observations to watershed scale fluxes. *Journal of Geophysical Research*, 114(G2), 1–14. doi:10.1029/2008JG000885
- Riveros-Iregui, D. a., McGlynn, B. L., Emanuel, R. E., & Epstein, H. E. (2012). Complex terrain leads to bidirectional responses of soil respiration to inter-annual water availability. *Global Change Biology*, 18(2), 749–756. doi:10.1111/j.1365-2486.2011.02556.x

- Riveros-Iregui, D. a., McGlynn, B. L., Marshall, L. a., Welsch, D. L., Emanuel, R. E., & Epstein, H. E. (2011). A watershed-scale assessment of a process soil CO₂ production and efflux model. *Water Resources Research*, 47, 1–12. doi:10.1029/2010WR009941
- Roe, A. and Amman, G. (1970). Mountain pine beetle in lodgepole pine forests. USDA Forest Service, Intermountain Research Station, Research Paper INT-71, 26 pp.
- Safranyik, L., Carroll, A. L., & Wilson, B. (2007). The biology and epidemiology of the mountain pine beetle in lodgepole pine forests. *The mountain pine beetle: a synthesis of biology, management and impacts on lodgepole pine*, 3-66.
- Samman, S. and Logan, J. (2000). Assessment and response to bark beetle outbreaks in the Rocky Mountain area. Report to Congress from Forest Health Protection, Washington Office, Forest Service, USDA. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-62, 46 pp
- Schmidt, W. C., & Friede, J. L. (1996). Experimental Forests , Ranges , and Watersheds in the Northern Rocky Mountains : A Compendium of Outdoor Laboratories in Utah, Idaho, and Montana.
- United States Army Corps of Engineers. 1956. Snow Hydrology: Summary Report of the Snow Investigations, US Army Corps of Engineers, North Pacific Division: Portland, OR.
- Varhola, A., Coops, N. C., Weiler, M., & Moore, R. D. (2010). Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*, 392(3-4), 219–233. doi:10.1016/j.jhydrol.2010.08.009
- Warren, S. G., & Wiscombe, W. J. (1980). A Model for the Spectral Albedo of Snow. II: Snow Containing Atmospheric Aerosols. *Journal of the Atmospheric Sciences*, 37, 2734–2745.
- Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase western US forest wildfire activity. *Science*, 313(5789), 940-943.
- Winkler, R., Boon, S., Zimonick, B., & Baleshta, K. (2010). Assessing the effects of post-pine beetle forest litter on snow albedo. *Hydrological Processes*, 24(6), 803–812. doi:10.1002/hyp.7648
- Wood, D. L. (1982). The role of pheromones, kairomones and allomones in the host selection and colonization behavior of bark beetles. *Annual Reviews of Entomology*, 27(411-46), 411-445

Woods, S. W., Ahl, R., Sappington, J., & McCaughey, W. (2006). Snow accumulation in thinned lodgepole pine stands, Montana, USA. *Forest Ecology and Management*, 235(1-3), 202–211. doi:10.1016/j.foreco.2006.08.013