RELATIONSHIP OF FIELD AND LIDAR ESTIMATES OF FOREST CANOPY COVER WITH SNOW ACCUMULATION AND MELT

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ABSTRACT

At the Priest River Experimental Forest in northern Idaho, USA, snow water equivalent (SWE) was recorded over a period of six years on random, equally-spaced plots in ~4.5 ha small watersheds (n=10). Two watersheds were selected as controls and eight as treatments, with two watersheds randomly assigned per treatment as follows: harvest (2007) followed by mastication (2008), harvest (2007) followed by prescribed fire (2008), prescribed fire alone (2006), and prescribed fire (2006) followed by salvage (2007). Canopy closure was recorded using a digital hemispherical camera, and snow water equivalent (SWE) was measured with a Polyvinyl chloride (PVC) snow tube before and after treatments. In addition, canopy densities derived from two LiDAR datasets taken at the beginning and the end of the study were compared to the hemispherical photos. The objectives of the study were to 1) assess changes in snow accumulation and melt as a result of changes in canopy cover, and 2) compare the digital photograph method and LiDAR for quantifying canopy cover changes. A Before-After/Control-Impact (BACI) analysis was conducted to examine how the reduction in canopy cover due to treatments influenced the snow accumulation and melt. The BACI assesses an experimental design in which measurements are made on both control and impacted experimental units before and after prescribed treatments. Such a design is often used to account for natural temporal variations that occur regardless of the treatment applied. Within the BACI framework, mixed-effects models were tested where Before/After and Control/Impact were considered fixed effects while the variable year was kept as a random effect. The results showed that there was an effect of the treatments on the SWE for the watersheds that received a thinning operation while no effect on the snowmelt was detectible. Field canopy estimates were significant in the models applied to the thinned watersheds while LiDAR estimates, although correlated (p = 0.66, 0.58, 0.77, and 0.62, for *Treatments 1*, *2*, *3*, and *4*, respectively) to the field estimates, had no significance in the statistical models. Some of the statistical models mildly violated assumptions of normality and equal variance, so further work is needed in order to correct for these violations. (KEYWORDS: canopy, SWE, snowmelt, LiDAR).

INTRODUCTION

In forested watersheds, canopy cover greatly affects snow accumulation and melt rate. Most often a decrease in canopy cover results in an increase in snow accumulation and an increase in melt rate where the radiative energy component is dominated by shortwave radiation. In contrast, an increase in canopy cover intercepts more snow before it reaches the ground and thus generally results in less accumulation and lower melt rates. The processes of snow accumulation and melt have particular implications in managed watersheds where activities such as timber harvest and prescribed burning occur. Harvesting is widely perceived as a method to conserve water in different environments. In watersheds dominated by snow processes, forest treatments—described as either clear-cuts or as patches of open areas within the forest canopy—have also been proven to increase water yield (Golding and Swanson, 1986).

Both snow accumulation and melt processes take place differently on south versus north slopes. After harvest, there is typically an increase in snow accumulation on both slopes, but with southern slopes accumulating less snow compared to northern slopes (Packer, 1962; Haupt, 1979; Woods et al., 2006; Jost et al., 2007).

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Snow accumulation or melt also depends on the spatial arrangement of tree removal. For example, Woods et al. (2006) studied two types of treatment: a thinning where all remaining trees were evenly distributed and another where the trees were grouped on 0.2–0.8 ha with intervening corridors. The results showed that on a south-facing slope that accumulated more snow, the gain could be offset by an increase in sublimation due to an increase in wind speed and solar radiation. In another study in Montana, a 9% increase in snow water equivalent (SWE) was found for two sites: burned and clear-cut compared to a mature forest with a 42% canopy cover (Skidmore et al., 1994). Even though elevation, aspect, and slope were included as control variables, the analysis was only able to explain 43% of the variation in comparing burned and unburned sites. The authors attributed the remaining variation to differences in ground cover and microclimate variability. Similar results were found by Winkler et al. (2005) in southwestern British Columbia where there was on average 23% less SWE in a mature-fir stand than in a clear-cut in early April, and melt rates in the former were 40% higher than in the latter. Smaller effects of canopy cover on SWE have been reported in areas with deep snowpack in comparison to areas with shallower snowpack (Harestad and Bunnell, 1981; D'Eon, 2004).

Creating openings in forests will increase snow accumulation as most of the snow that would normally be intercepted by canopy would reach the ground instead. Tree heights between 1H and 6H (where H is the surrounding tree height) have been reported as optimal for generating an increase in SWE (Golding and Swanson, 1978) or about 1.5*H* to 2*H* to maintain low melting rates (Golding and Swanson, 1978; Lawler and Link, 2011). The size of the canopy gaps is important since it controls the amount of both short- and long-wave radiation that passes through the canopy, which is important for snowmelt. Depending on latitude and time of year, these gaps can be shaded and can act as 'cold holes' keeping the snow longer on the ground (Bernier and Swanson, 1993; Lawler and Link, 2011).

Manipulation of the forest canopy is a common silvicultural practice not only for managing snow accumulation and melt but also for controlling the growth and development of desirable plants (Jennings et al., 1999). Changes in canopy structure can be derived from field measurements, spectral analysis, and LiDAR estimates; the preferred method depends on the canopy density, the extent of the study area, and accessibility. Three different concepts are considered when referring to forest canopy: canopy cover, canopy closure, and canopy density. Canopy cover refers to the presence or absence of the tree canopy projected vertically above the ground. Canopy closure refers to the proportion of sky hemisphere obscured by vegetation when viewed from a single point. Canopy density refers to a three-dimensional distribution of the canopy within a volume of space above the ground (Jennings et al., 1999; Paletto and Tosi, 2009; Smith et al., 2009). These three canopy measures will have different effects on snow accumulation and ablation. Canopy cover and canopy density will be more important for snow accumulation, while canopy closure and canopy density will mostly affect snow melt since in the last two cases both short- and long-wave radiations, the main driven factors for snow melt, can penetrate the canopy at different angles.

In this study we use the term canopy cover when we refer to the tree canopy in general, otherwise we use canopy closure or canopy density whenever we discuss one of the two methods used to characterize the canopy structure. The objectives of the study were to 1) assess changes in snow accumulation and melt as a result of changes in canopy cover, and 2) compare a hemispheric photograph method and LiDAR for quantifying canopy cover changes.

Study Site

The study area is located in the Priest River Experimental Forest, in northern Idaho, USA (Fig. 1). Ten small watersheds, with an average area of 4.5 ha, were selected in a paired watershed study to test the effects of canopy cover on snow accumulation and melt. The watersheds are situated on southern aspects at an elevation between 843 and 1236 m a.s.l. and have an average slope of 29 percent. Elevation and aspect are known to have an influence on the amount of snow accumulation and melt due to differences in the solar angle (Ellis et al., 2011). The southern aspect for all watersheds was intentionally chosen to minimize the possibility of finding differences in snow accumulation and melt due to factors other than changes in canopy cover.

The tree canopy at the study site is mostly comprised of grand fir, Douglas-fir, ponderosa pine, western red cedar, and western larch. The climate is transitional between northern Pacific maritime and continental types with a mean annual temperature of 7°C and average annual (water year) precipitation of 817 mm.

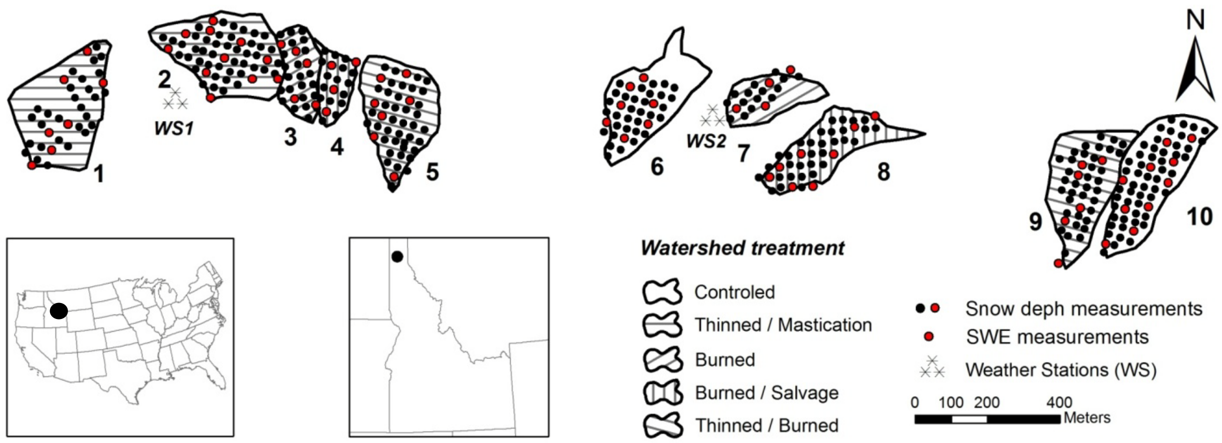

Figure 1. Location of the study site and sampling scheme

Treatments

Paired watersheds were selected based on similarities in topography and past silvicultural interventions and received one or two of the following treatments: (1) thinned (2007)/mastication (2008), (2) burned (2006), (3) burned (2006)/salvage (2007), (4) thinned (2007)/under-burned (2008), and (5) controlled. For simplicity, we will refer to these Treatments as *1*, *2*, *3*, *4*, and *5* hereafter.

Sub-Treatments

Additional groupings were established based on elevation, and data were analyzed based on similarities in topography and past silvicultural interventions and received one or two of the following treatments: (1) thinned (2007)/mastication (2008), (2) burned (2006), (3) burned (2006)/salvage (2007), (4) thinned (2007)/under-burned (2008), and (5) controlled.

METHODS

Snow Measurements

Both SWE and snowmelt have a high ground variability in mountainous forested regions. Consequently, sampling schemes at scales <100 m have been suggested for conducting snow accumulation studies (Watson et al., 2006). In our study, a sampling grid with a 30-m spacing was applied for each watershed (Fig. 1). The number of points within each watershed ranged between 19 and 62 depending on the size of the watershed, so that sampling intensity was consistent. In total, there were 383 sampling locations that were indicated with a stake. Between 2004 and 2010, from early February through April or May, snow depth was measured twice per month at each sampling location using a graduated marked rod to characterize conditions near peak snow and during the mid-melt phase. A total of 70 snow density measurements were made using a low-cost snow tube (based on the Adirondack snow tube, http://www.erh.noaa.gov/btv/html/snowtubeinstr.htm) at randomly selected points within each watershed. An average snow density was obtained for each watershed on each sampling day, and multiplied by the snow depth at each location to estimate SWE.

Snowmelt was calculated as:

$$\begin{cases} (SWE1 - SWE2)/n & if\ SWE1 > SWE2 \\ 0 & if\ SWE1 \leq SWE2 \end{cases} \quad (1)$$

where $SWE1$ and $SWE2$ represents the SWE for the first and second dates, respectively, and n is the number of days between these two dates. Snowmelt was set to zero if snow accumulation has occurred between two consecutive sampling dates. In between snow measurements there could be alternating episodes of snow accumulation and melt; therefore, Eq. 1 renders a net value of snowmelt over the period between two measurements.

Canopy Data

Field canopy closure was recorded using a Pentax K100D digital hemispherical camera with a Pentax 17 mm fisheye lens. The majority of the photos were taken early in the morning, late in the evening, or during cloudy days to obtain a better contrast. The photos were taken at 1.5 m above the ground looking upward with the camera oriented toward the north and were obtained using both a standard film and a digital camera. The actual position of the measurement plots was chosen to coincide with the location of the SWE measurements. The interpretation of the hemispherical photos was conducted using Hemiview software (www.delta-t.co.uk). Three series of photos were taken at breast height above the ground, and were assigned to the study period as in Table 1.

2004 2007 2007

Figure 2. Example of canopy closure photos for Watershed 8, plot 3: (a) before treatment, (b) after the wildfire simulation, and (c) after salvage.

For comparison with the field canopy closure photos we used pre-study and post-study canopy density measures derived from LiDAR point cloud data collected in 2002 and 2011, respectively (Fig. 3). The LiDAR data were collected at a post spacing of 3 m in 2002 and 0.5 m in 2011. Canopy density was calculated across the landscape as the number of LiDAR returns above breast height (1.37 m) divided by the total returns, within 20 m × 20 m cells (Fig. 3) (Evans et al. 2009). A consistent output resolution of 20 m was used to allow for direct comparisons between 2002 and 2011 and a consistent vegetation height threshold of 1.37 m above ground to facilitate comparisons to the canopy closure measures also collected at breast height (Smith et al. 2009).

Table 1. Assignment of yearly canopy values for the study period.

WS	TR	TR description	Canopy	Field and LiDAR canopy values					
				2004	2006	2007	2008	2009	2010
1, 2	1	Thinning (2007) Mastication (2008)	field						
			LiDAR						
3, 7	2	Burned (2006)	field			†	†	†	†
			LIDAR						
4, 8	3	Burned (2006) Salvage (2007)	field						
			LIDAR			NA			
5, 9	4	Thinning (2007) Underburn (2008)	field						
			LiDAR						

WS = watershed; TR = treatment; † = missing photos for WS 7; NA = not available

field — Photo 1 (11/2004); Photo 2 (09/2007); Photo 3 (11/2007)
LiDAR — Year 2002; NA No image; Year 2011

RESULTS AND DISCUSSION

In general, the decrease in canopy cover was observed in both field and LiDAR data sets (Table 2). For Watershed 7, the field photos after the treatment were missing, and, for Watersheds 4 and 8, we did not have an intermediate LiDAR image for year 2007, after the burning treatment.

Modeling the Effects of Canopy Cover on Snow Accumulation

In the case of *Treatment 1* (Thinned/Mastication) an interaction between Period (Before/After) and Treatment (Control/Impact) was indicated by all three models, suggesting a difference between the amount of snow accumulation before and after treatments. As the interaction term was significant, we further investigated the BACI contrasts for differences among the three periods (before any treatment, after thinning, and after mastication). More accumulation was observed after the thinning treatment, which was statistically different from the period before any treatment. Additionally, a significant decrease in the amount of snow accumulation was observed after the mastication in comparison to thinning and no difference was observed between the period before any treatment and after mastication.

For *Treatments 2 (Burned)* and *3 (Burned/Salvage)* the interaction term was not significant for all three models, meaning that the burning treatment or the combination of burning with salvage had no effect on the snow accumulation.

The only significant interaction for *Treatment 4* (Thinned/Burned) was observed for the SWE model containing field canopy closure. The results of the BACI contrast showed an increase in SWE before and after the thinning treatment. No difference was observed when comparing SWE or snowmelt before any treatment and the burn treatment or between the thinning and burn treatments.

Table 2. Least-Square Means indicating differences in canopy cover, SWE, and snowmelt, before and after treatments. T1 to T4 denote the number of treatments, and SWE and SM snow water equivalent and snowmelt, respectively.

		Field Canopy (% cover)	LiDAR Canopy (% cover)	LS Means	
				SWE (mm)	SM (mm day^{-1})
T 1	Before*	61.3	64.0	54.2	1.9
thinned (2007)	After (1)*	43.4	48.8	169.3	3.5
mastication (2008)	After (2)*	43.3	48.8	38.4	1.9
T 2	Before †	58.0	71.4	44.4	1.8
burned (2006)	After †	52.6	39.4	76.0	2.1
T 3	Before ‡	66.2	82.9	43.1	1.9
burned (2006)	After (1) ‡	44.1	.	58.0	1.6
salvage (2007)	After (2) ‡	26.7	22.0	91.3	2.6
T 4	Before §	70.5	74.1	56.0	1.8
thinned (2007)	After (1) §	50.0	45.8	174.5	3.4
underburned (2008)	After (2) §	50.0	45.8	42.0	2.1

* *Before = 2004, 2006, 2007; After (1) = 2008; After (2) = 2009, 2010*
† *Before = 2004, 2006; After = 2007, 2008, 2009, 2010*
‡ *Before = 2004, 2006; After (1) = 2007; After (2) = 2008, 2009, 2010*
§ *Before = 2004, 2006, 2007; After (1) = 2008; After (2) = 2009, 2010*
. = missing data

Modeling the Effects of Canopy Cover on Snowmelt

No significant interaction was found between Period (Before/After) and Treatment (Control/Impact) for any of the treatments, with or without canopy. If snow accumulation is mostly influenced by the presence/absence of a certain canopy structure and the different gap widths within the canopy, snowmelt process is more complex and is driven mostly by radiation (Link and Marks, 1999; Pomeroy et al., 2009). Forest canopy can decrease the melting process by shading the snow cover areas, or in contrast, can increase it under certain conditions (Li et al., 2008). Snowmelt is not only influenced by the direct shortwave radiation above the site of interest, but also by the canopy that lies within the solar beam path (Lawler and Link, 2011) making this process even more complex. Substantial differences between sub-canopy air, needle-branch, and trunk temperature have been reported with the largest differences being in small gaps within discontinuous canopies (Pomeroy et al., 2009), and so adding in the statistical models just the canopy cover without other additional variables that are influencing the whole radiative component might explain the lack of statistical significance in our models.

Statistical Correlations

Snowmelt was not correlated with any of the two forms of canopies; however, it was negatively correlated to SWE with *p*-values of −0.11, −0.12, −0.14, and −0.14, for *Treatments 1*, *2*, 3, and *4*, respectively. The negative correlation means that snowmelt increases with a decrease in SWE. This statement holds since snowmelt starts later in the season after the snow has accumulated. SWE was negatively correlated with field canopy closure for *Treatments 3* ($p = -0.11$) and 4 ($p = -0.10$), and positively correlated to the LiDAR canopy densities for Treatments 1 ($p = 0.06$) and 2 ($p = 0.08$), all at $\alpha<0.05$.

Field canopy closure was statistically significant in the models for all treatments, while the LiDAR canopy density was not significant. However, for all treatments the two measures of canopy (canopy and LiDAR) were highly correlated (p = 0.66, 0.58, 0.77, and 0.62, for *Treatments 1*, *2*, *3*, and *4*, respectively). The lack of significance for the LiDAR canopy in the statistical models may be due to the spatial resolution of the LiDAR canopy density images and should be further investigated to find an optimal resolution compatible to the scales at which SWE and snowmelt were measured. In a previous study, the LiDAR returns were calculated at a 2500 m^2 scale to match the resolutions of snow surveys that were conducted at 50 m × 50 m (Varhola et al., 2010). The results showed a stronger correlation of snow accumulation with LiDAR canopy estimates than with field canopy estimates. The strong relationship in this study was likely attributed to the good match between the spatial resolutions of the LiDAR images and the snow surveys.

CONCLUSIONS

A BACI assessment was made to determine the influence of four treatments on snow accumulation and melt rate at ten small watersheds in the Pacific Northwest. This analysis allowed us to look simultaneously at the interaction of the Before/After treatments with the Control/Impacted watersheds while taking into consideration variations in the snow accumulation and melt between the years.

The major observed differences were for SWE for *Treatments 1* and *4*, between the period before any treatment and the thinning treatment. Since the thinning period was only during 2008, which was a wet year with a large amount of precipitation in the form of snow, it might be that the differences in snow accumulation were more extreme in years with high annual precipitation and not necessarily due to the treatments. Inconsistencies in the amount of snow accumulation due to experimental time has been reported by other researchers (Winkler and Moore, 2006; Woods et al., 2006; Jost et al., 2007). These studies showed that the effect of forest cover is more pronounced during years with lower precipitation and less pronounced during average years. For example, Woods et al. (2006) found no statistically significant difference between watersheds that received a thinning treatment and control watersheds for years with less snowfall.

The greater SWE after thinning treatments observed in this study was not enough to generate an increase in runoff from these small watersheds, as reported by another study (Elliot and Glaza, 2008) conducted in parallel to this one. This could be the result of deeper soils that overlay permeable bedrock and are resistant to erosion (Elliot and Glaza, 2008), which could facilitate water infiltration.

In total, we ran 24 models (three for both SWE and snowmelt for each of the four treatments). Analyzing the diagnostic plots for each of the 24 models revealed mild violations of either the assumption of normality of the residuals, equal variance, or both. Our future efforts to better understand the relationship between field and LiDAR estimates of canopy structure with snow processes will include a rescaling of the LiDAR images to different resolutions (e.g., 5- and 10-m resolutions) and applications of relevant transformations to the data set in order to ensure normality and equal variance for all models.

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