THE INFLUENCE OF A HETEROGENEOUS MIXED-CONIFER CANOPY ON SNOW ACCUMULATION AND MELT

Eryn E. Schneider[1], Andrew J. Larson [1], and Kelsey G. Jencso[1]

ABSTRACT

The patterns of snow accumulation and ablation have been linked to the timing and quantity of available water in the semi-arid forested mountain watersheds. Forest patterns are often used as surrogates for processes where we expect that spatially recognizable structures give rise to ecohydrological processes. Forest canopies exhibit heterogeneity manifested as a mosaic of differing species, spatial arrangements, and canopy densities that differentially intercept precipitation and absorb or reflect radiation; thereby controlling the processes of snow accumulation and ablation. In this study we examined how heterogeneous canopy structure influenced the spatial variability of snow water equivalent (SWE) and disappearance date. High resolution, empirical snow measurements were collected at peak accumulation and monitored regularly throughout the melt season on two, 4.48 ha, fully georeferenced, mixed-conifer plots in western Montana. In 2014, peak accumulation occurred on March 18 and snow lasted 48 days with peak snow water equivalent ranging from 0 -17.9 cm. Percent canopy cover ranged from 0-86%. Higher canopy density areas had lower snow accumulation and earlier disappearance dates. By linking canopy patterns to specific snow processes, we will be able to improve process based models to provide more accurate predictions of water availability. Model predictions can be scaled up to management relevant scales and provide managers with empirical management recommendations for optimizing water resources given climate change and increased drought. (KEYWORDS: mixed-conifer forest, forest canopy, spatial heterogeneity, snow water equivalent, snow disappearance date)

INTRODUCTION

A third of the Earth's surface experiences seasonal snow cover which serves as a reservoir that sustains hydrological and ecological processes throughout the growing season. In the semi-arid mountainous west, the annual spatial and temporal distribution of snow accumulation and melt in forested watersheds controls the timing and quantity of available water, influences surface-atmosphere energy fluxes, and ground temperatures, while providing 60 to 90% of the annual input into the terrestrial hydrologic cycle (Troendle, 1983; Jost et al., 2007). Thus, the ecosystem services provided by these forested watersheds are vital for biological, social and economic health.

Most of the seasonally snow-covered watersheds in the western United States are forested (Winkler et al., 2005). The forest canopy can be characterized as an intercepting, radiating body that extends over the snow surface and projects a heterogeneous and complex structure into the atmosphere (Jeffrey, 1968). In addition, the structure of the forest canopy varies in time and space affecting patterns of snow accumulation and ablation by intercepting potentially large quantities of falling snow, modifying local wind patterns and snow redistribution, and interacting with the surface energy balance by absorbing shortwave radiation and emitting longwave radiation (Faria et al., 2000**;** Winkler et al., 2005; Woods et al., 2006; Jost et al., 2007; Musselman et al., 2008; Lundberg and Halldin, 1994; Hedstrom and Pomeroy, 1998). Within forested stands, heterogeneity is manifested as a mosaic of differing species compositions, tree age, sizes and arrangements, and alternating canopy densities. These characteristic patterns are intrinsically related to how each stand functions (Boyden et al., 2012). Vegetation patterns have been used as surrogates for processes where we expect that spatially recognizable structures give rise to ecological process. It stands to reason than that the high within plot variability in snowpack properties in both time and space should be linked to the overlying forest structural heterogeneity (Elder et al., 1991; Davis et al. 1997; Pomeroy et al., 1998; Jost et al., 2007). Empirically, canopy characteristics have been found to explain up to half of the variation in season snowpack accumulation and ablation (Moore and McCaughey, 1997; Varhola et al., 2010; Musselman et al., 2012).

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The need for, and the value of high-resolution empirical data from forested, snow-dominated systems is becoming more important as the frequency of modeling studies increases and managers and scientists realize the limitations of current collection and prediction methods. Currently, predictions of melt timing and magnitude for water resource management are often parameterized using information gathered from ground-based methods (e.g., SNOTEL, snow courses) or remote sensing images. Existing snow courses and telemetry sites are established in open areas or forest clearings. However, most of North America's watersheds are forested and impose highly variable patterns of snow accumulation and ablation (Pomeroy et al., 2002; Varhola et al., 2010; Meromy et al., 2013). Other estimates use satellite images to make these predictions, but this method is limited by the inability to observe the variability of snow accumulation and ablation patterns. Here, estimates become more uncertain as the density of the canopy increases and often the scale of individual pixels is too coarse to capture the scale at which the controlling processes are occurring (Pomeroy et al., 2002). Understanding snow processes at the tree neighborhood scale is critical for accurately parameterizing spatially explicit process based models, designing optimal sampling schemes and for monitoring silvicultural manipulations (Winkler and Moore, 2006).

Our objective was to conduct an initial analysis of high-resolution manual snow measurements collected within a heterogeneous mixed-conifer canopy for the winter of 2014. Utilizing this data we sought to: (1) determine how spatially variable peak snow water equivalent (SWE) and snow disappearance date (SDD) are beneath the forest canopy; and (2) how much of the observed variation in SWE or SDD can be explained by a simple model of total canopy cover.

METHODS

Study Area

The study area was located in a mixed-conifer forest at Lubrecht Experimental Forest, 50 km northeast of Missoula, MT in the Blackfoot River basin (47° North latitude, 113° West longitude; Figure 1). The study site is at 1,250 m with generally flat topography. Mean annual temperature is $7^{o}C$ with an average of 15.3 cm of snow water equivalent (1971-2015; Nimlos, 1986) accumulating from November to March. Forests are dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) with lesser components of western larch (*Larix occidentalis*) and lodgepole pine (*Pinus contorta*). Forest are primarily second-growth (80-90 years) following heavy harvesting of trees larger than 30 cm in the early 1900's (Fiedler et al., 2012).

Data Collection

Vegetation

Vegetation was fully georeferenced on two, 4.48 ha plots. All trees greater than 10.0 cm at breast height (1.37 m) were tagged with a unique identifier and their x, y locations mapped using a surveyor grade total station. Structural characteristics measured on each individual used for this analysis were species and diameter at breast height (DBH).

Snow

High-resolution, empirical snow measurements were collected along a systematic grid (20 m x 20 m) and 15 intensive plots at peak accumulation and monitored regularly throughout the melt season (Figure 2). Intensive plots were measured at 1 m intervals on 2, 9 m transects placed 90^{o} apart. Snow depth and densities were collected at 405 locations per plot with sampling distances ranging from 1-20 m at peak accumulation. Empirical snow depth and density values were used to calculate snow water equivalent (SWE). Snow disappearance date was recorded as a snow presence/absence value at every meter along 15, 160 m transects formed by grid columns at 3 day intervals from peak accumulation until all snow had melted from the plot.

Data Analysis

An exponential variogram model and ordinary kriging were used to evaluate the spatial variation of peak SWE across each plot. Kriging was used because it is an interpolation method that utilizes distances and correlation structure within the empirical data (Cressie, 1993,
Fortin et al. 2002).

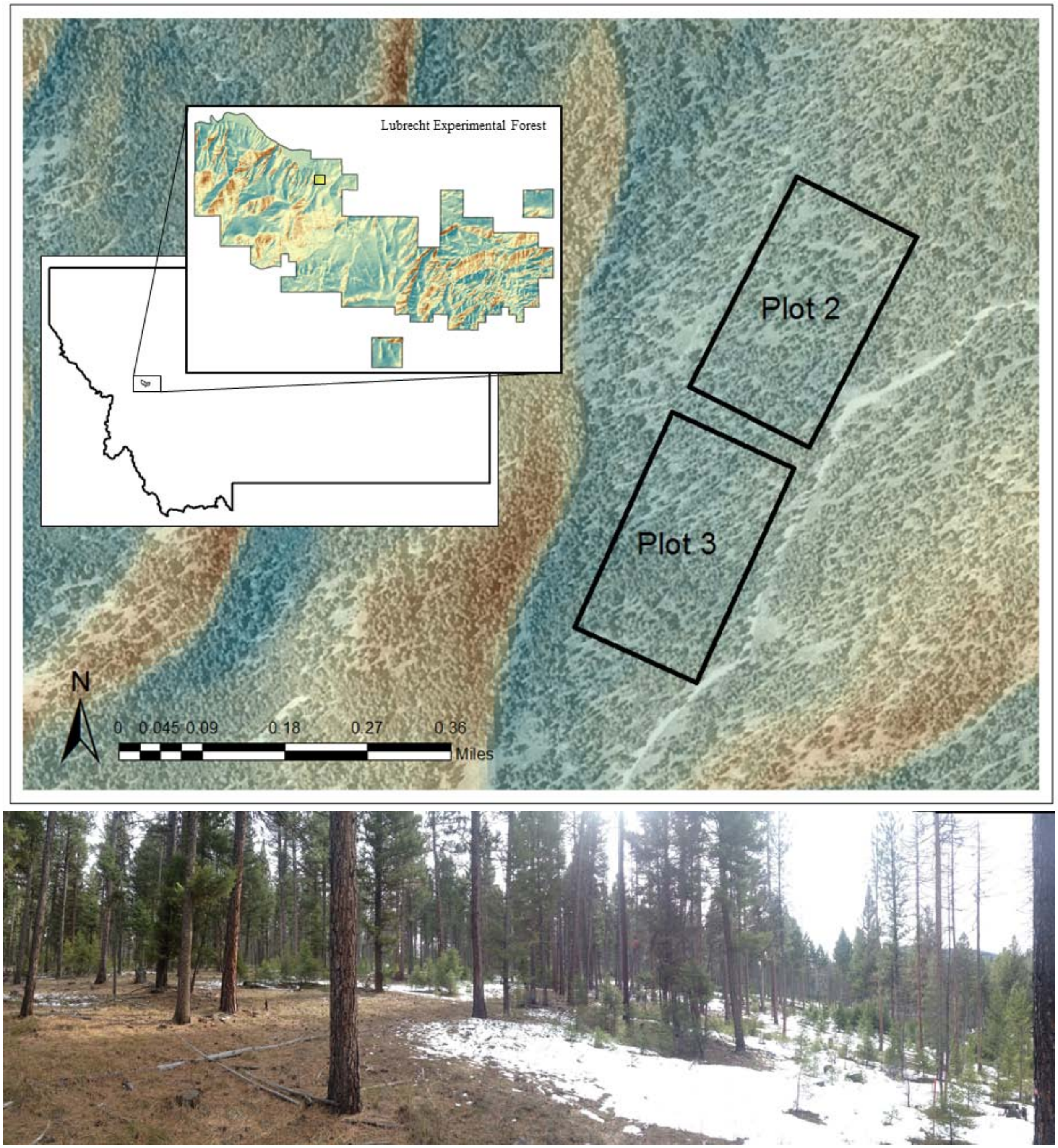

Figure 1. Study plots located in western Montana within the Lubrecht State Experimental Forest within heterogeneous mixed-conifer forests. Photograph of an example of the heterogeneity present in forest structure and variation in snow melt on March 5, 2015 within the study plots (photo: E.E. Schneider).

The relationship between variation in SWE and canopy structure was analyzed using an estimate of total canopy cover using maximum crown diameter estimates and ArcGIS. Species specific allometric equations between DBH and maximum crown diameter were used to estimate crown dimensions for each tree (Bechtold, 2004). In

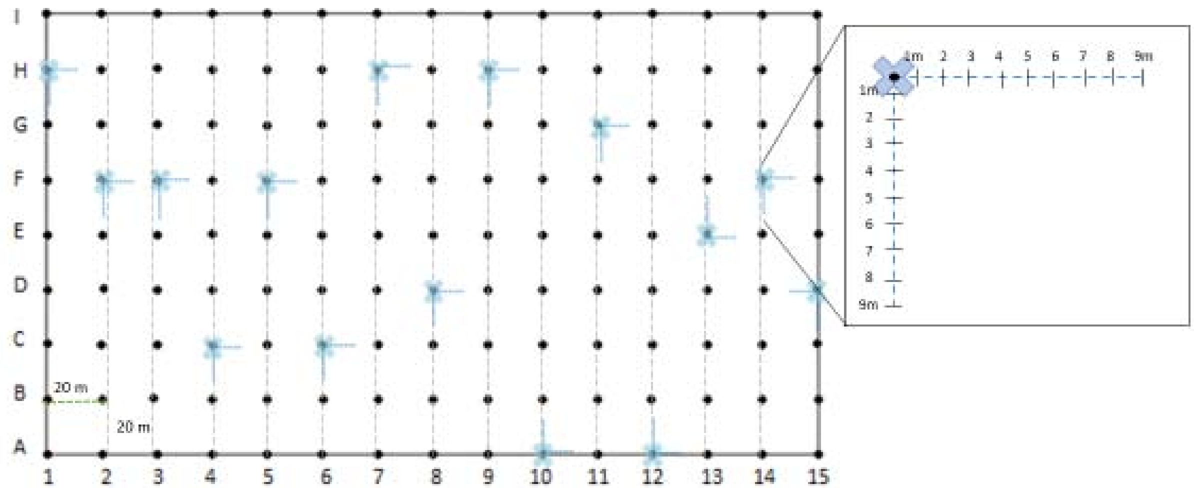

Figure 2. Plot layout and sampling design for 4.48 ha plots. Black circles are the junction points along the 20 m x 20 m grid. X's show the location of intensive sampling transects depicted in further detail in the expansion to the right. Melt surveys were sampled along vertical (grid columns) dashed lines.

ArcGIS, a 6 m radius sampling region was placed around each sampling point to estimate the local canopy cover (Figure 3). We determined the canopy cover at each sampling location by layering the projected tree crowns over the sampling regions in ArcGIS.

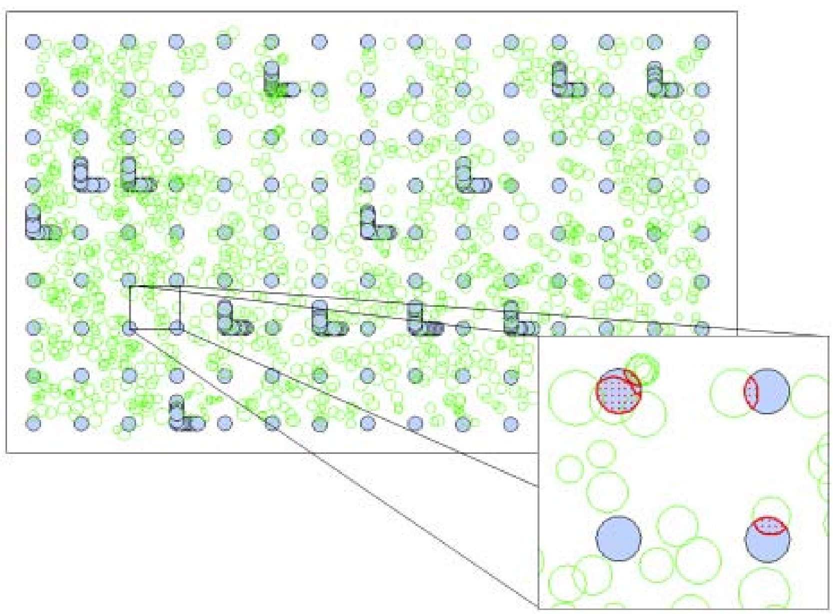

Figure 3. Map of layered sampling regions (solid fill circles) and maximum tree crown (open circles) where point size is proportional to size of the crown. The subregion illustrates the area of crown cover (dotted area) within each sampling region.

RESULTS

Variation in SWE and SDD

We observed a range of values for both peak SWE and the date of snow disappearance collected beneath a heterogeneous canopy. Peak snow water equivalent on March 18 was normally distributed with a range from 0-16.4 and 0-17.9 cm during the winter of 2014, with a mean of 8.2 and 8.7 cm for plot 2 and 3 respectively (Figure 3). The coefficient of variation was 0.31 for plot 2 and 0.40 for plot 3. Figure 4 provides a visual illustration of the spatial variation in SWE across both plots using ordinary kriging. Snow disappearance dates ranged from 0-48 days from the date of peak snow accumulation.

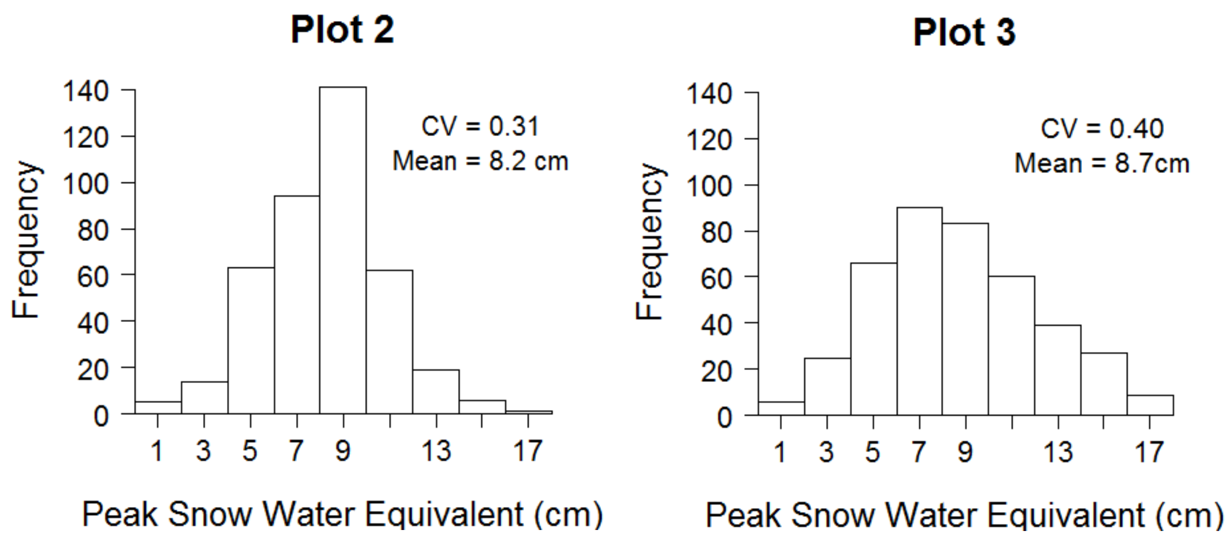

Figure 4. Distribution of peak snow water equivalent in 2 cm classes for 405 sampling regions per plot. CV is coefficient of variation.

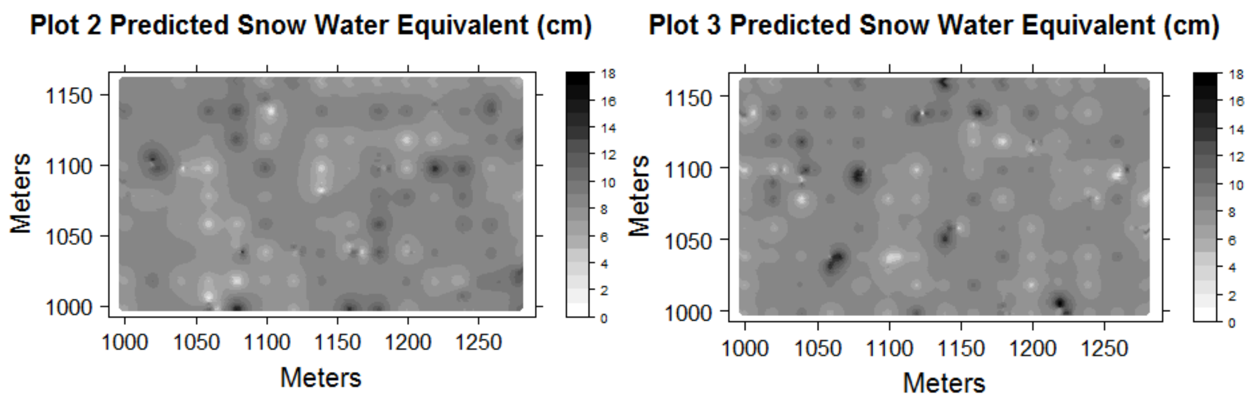

Figure 5. Spatial distribution of SWE across the plots using ordinary kriging.

Variation Explained by Forest Canopy Cover

Forest canopy cover exhibited a range across sampling regions that explained about 20% of the variation in peak SWE and SDD. Crown cover ranged from 0-85.7% and 0-89.3% with a mean of 34.9% and 31.6% for plots 2 and 3 respectively (Figure 6). Peak snow water equivalent decreases with an increase in canopy cover with total canopy cover accounting for 8% in plot 2 and 19% in plot 3 (Figure 7). Canopy cover accounts for 19-22% of the variation in snow disappearance date where canopy cover and SDD are negatively related (Figure 8). In areas with high canopy cover there tends to be less SWE and it melts earlier than more dense areas.

CONCLUSIONS

The high-resolution snow measurements and fully georeferenced forest data from this analysis represent an unprecedented dataset to examine within forest snow characteristics and processes. Analysis indicates that the scale of structure in the spatial distribution of peak snow water equivalent follows the scale of structure of tree crowns; small scale variation in SWE is consistent with small scale heterogeneity in canopy structure. Peak SWE was found

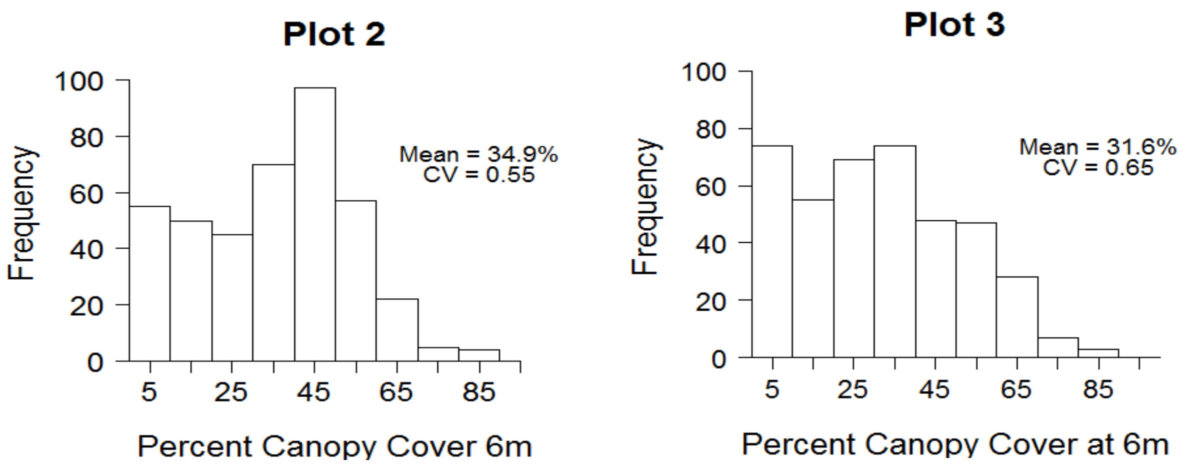

Figure 6. Frequency (%) of canopy cover over 405 sampling regions per plot in 10% cover classes. CV is coefficient of variation.

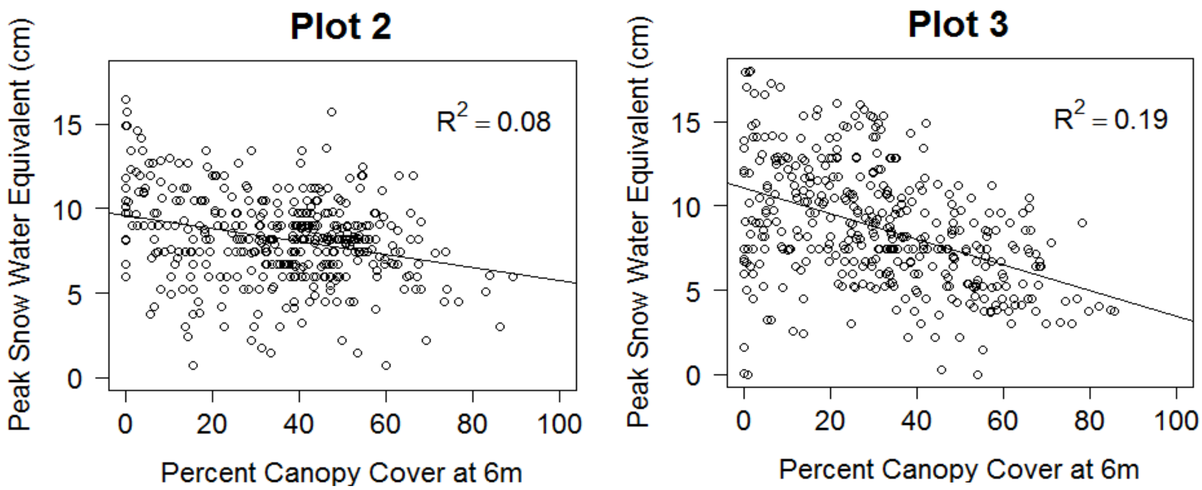

Figure 7. Peak snow water equivalent as a function of percent canopy cover at 405 sampling regions per plot for the winter of 2014.

to be autocorrelated at distances equivalent to an individual crown or small group of trees (> 17-19 m); this distance is consistent with previous studies (Moore and Winkler, 2006). Our results are consistent with previous work in other regions (Varhola et al., 2010; Moore and McCaughey, 1997) and the intuitive assumption that areas with high canopy cover tend to accumulate less snow, and thus SWE, primarily due to interception and earlier melt due to the tree's influence on the energy balance. However, Lundquist et al. (2013) point out that this trend holds for regions with warmer, wetter winter climate regions and is opposite for more continental regions with cold, dry winters.

Quantifying the variation in the distribution of SWE and SDD is critical for accurate forecasting of quantities and timing of available water resources. In a changing climate where forecasts are for less snow and earlier melt in the drought-prone west, managing for forest health and critical water resources go hand in hand (Elsner et al., 2010). By linking canopy structures and patterns to specific snow processes we may be able to improve process-based models to provide more accurate predictions of water availability. With improved mechanistic understanding, models can then be scaled up to management relevant scales and provide forest and water resource managers with empirical management recommendations for optimizing water resources given climate change and increased drought. For example, forest restoration and fuels reduction treatments that reduce canopy cover and create openings through thinning and gap creation will enhance snow accumulation, retard melt, and create heterogeneity which encourages resistance and resilience in forests (Churchill et al., 2013).

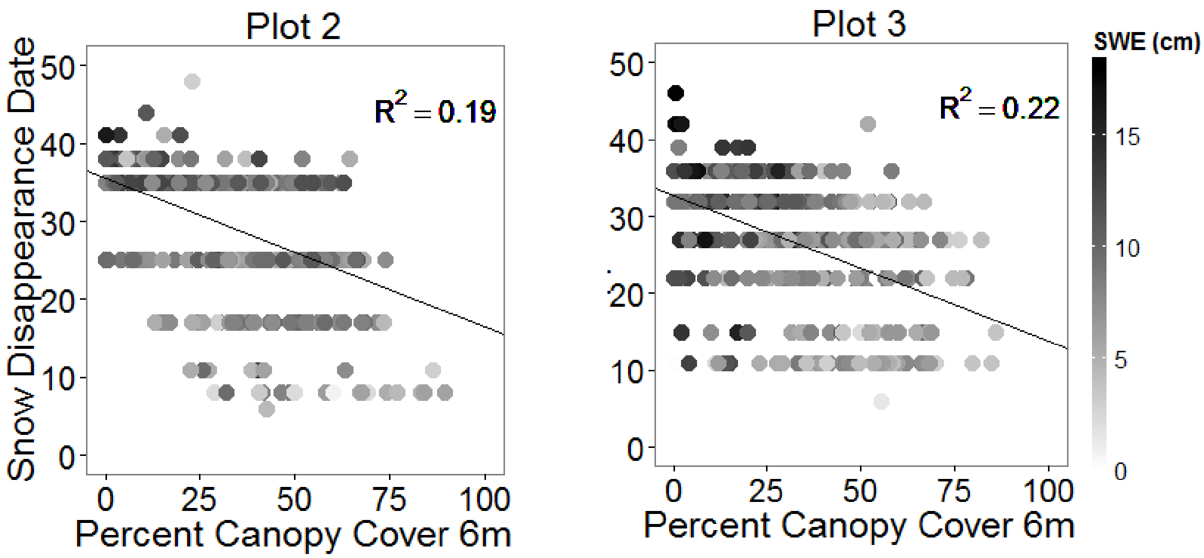

Figure 8. Snow disappearance date as a function of percent canopy cover and peak SWE at 405 sampling regions per plot. Snow disappearance date is given as days from peak accumulation. Data points have a color gradient that corresponds to the amount of peak SWE observed at each sampling region.

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