Title

Influence of within-stand tree spatial arrangement on snowpack distribution and ablation in the Sierra Nevada, CA

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Publication Date
2015

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA, MERCED

Influence of within-stand tree spatial arrangement on snowpack distribution and ablation in the Sierra Nevada, CA

A Thesis submitted in partial satisfaction of the requirements for the degree of Master of Science

in

Environmental Systems

by

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2015

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2015

Dedication

This work is dedicated to my family,

who have supported me in all my endeavors,

helped me at my best and worst,

and have always believed in me.

To my wife and daughter who fill me with love and joy,

Stephanie and Annabelle.

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Acknowledgements

My time at University of California Merced has been a wonderful experience and I wouldn't have made it through without the support, guidance, and patience from my advisor Dr. Roger Bales. I owe a very large thank you to both Dr. Robert Rice and Dr. Martha Conklin for hiring me back in 2012 and inviting me into the Mountain Hydrology lab. I also need to acknowledge and thank the SNRI staff for helping me out countless times on problems ranging from expense reports to major career and life decisions. Thank you to the Mountain Hydrology lab, which is made up of a wonderful group of individuals, all of whom I have learned many lessons from, and who have helped me grow personally and professionally.

I would like to thank Dr. Eric Knapp from the USFS Pacific Southwest Research Station for designing and implementing the Variable Density Thinning Study. In addition, I'd like to thank Dr. Knapp for his technical advice, help in the field, taking all the hemispherical-photographs, and greatly assisting me with both the analysis of data and the writing of this thesis. Bob Carlson, also with the USFS PSW, was also incredibly valuable out in the field and I am grateful for the assistance he provided. The USFS Summit Ranger District of the Stanislaus National Forest was very helpful and cooperative with all of my requests for access into the project site, specifically Maria Benech.

In addition to all the help that was received from the USFS, I'd like to thank all the students and staff who assisted with technical advice and field operations that made this project possible. I'd like to thank Patrick Womble, Erin Stacy, Ryan Lucas, Gesha

Uminskiy, Tyler Patel, Charlie Carrillo, and Jefferson Laird of UC Merced for assisting with the snow surveys, installing the sensor nodes and erecting the meteorological towers. I'd like to thank Ziran Zhang of UC Berkeley for help programming the data loggers and assisting in all the de-bugging sessions. A big thank you also goes out to the many graduate students, who maybe didn't work on this project, but helped me make it through some of the tough and stressful times that are associated with graduate school.

I would like to thank my wife, Stephanie, for all her support and boundless patience as I pursued this degree. I consider myself lucky to have had such a wonderful and understanding companion alongside me on this journey and without her would most likely not have been able to complete the degree. In my time at UC Merced, I not only earned the title of Master of Science, but also that of father. I was lucky enough to be blessed with a beautiful daughter, Annabelle, while attending graduate school and am so excited to say that she was able to attend my thesis defense! I hope that she is able to pursue her dreams, whatever they might be, and hopefully my story will give her inspiration.

This research was funded through the USDA-NIFA grant 11-03859 to the Pacific Southwest Research Station.

Abstract

Much of the Sierra Nevada forests are overstocked with too many trees, are at risk of burning in stand-replacing wildfires due to the fuel loading, contain almost complete canopy coverage over the landscape and intercept a substantial portion of the snowpack, and in need of thinning. New research shows that forest thinning patterns allowing for forest structures comprising of clumps of varying density, single individual trees, and forest gaps are what the historic stands in Sierra Nevada were comprised of. In addition to returning the forest to historic stand structure, forest thinning will also allow for greater amounts of snowpack to reach the forest floor and persist longer into the season before complete meltout. This study set out to see if this new thinning spacing pattern would affect snow accumulation or ablation rates as compared with the current standard even-tree spacing. Data from four snow surveys, distributed light/temperature sensors, hemispherical photographs, and a small distributed network of snow-depth sensors were analyzed from three different forest treatments in the Sierra Nevada. The first treatment consisted of variable thinning, which reduced the stems per acre by 80%, the basal area per acre by 40%, and created a heterogeneous forest structure with small gaps and clumps of trees of varying density. The second forest treatment reduced the stems per acre and the basal area per acre stand down to similar levels as the variable thinning, however the residual trees were left to replicate a homogenous, even spacing. An unthinned control provided a comparison to pre-treatment conditions. Snow-survey data showed that approximately 10-20% more snow accumulated in the two thinning treatments than in the control. Differences in snow depth between the two thinning treatments were statistically insignificant. Snow-survey results also indicated that the variable treatments kept snow on the ground longer than the even treatments in the 2013 water year, which had a peak snow water equivalent (SWE) of 17.9 cm, and melted out at approximately the same time as the control units. In 2014 the peak SWE recorded was only 6.3 cm, both the variable and even treatments melted out at the same time, and the control units kept a steady snowpack for approximately 1-3 days longer. Data from snow-surveys, distributed light/temperature sensors and snow-depth sensors showed that more snow accumulated in the open than at the drip edge and under the forest canopy, and that melt rates are faster in the open than under the canopy. Our data showed that the variable treatment held the snowpack longer and exhibited a slower melt rate than did the even treatments indicating a possibility to retain substantial amounts of snow in the mountains longer if this thinning structure were to be implemented on a landscape level.

Introduction

The Sierra Nevada provides the state with approximately 60% of its water supply, with much of that coming from the forested areas. California water security relies heavily on the Sierra Nevada annual snowpack, both in quantity and persistence. Warming of winter temperatures and the extent of snowcover of mountainous regions in the Western United States threaten downstream users (Mote et al., 2005; Mote, 2006; Diffenbaugh et al., 2015). Not only is there great need for accumulating more snowpack in the Sierra Nevada, but maintaining the snowpack on the ground longer is of critical importance. Westerling et al., (2006) showed that an earlier snowmelt leads to increased wildfire activity, and many Sierra Nevada water managers rely on summer snowmelt to keep their reservoirs full in the hot, dry late-summer months. The current snow-measurement instrumentation in the Sierra Nevada, established decades ago, is based on a relatively small number of snow-survey and snow-pillow sites. These are indices of the actual snow loading found across the Sierra Nevada, rather than representative, quantitative measures (Bales et al., 2006; Rice et al., 2011). Understanding and predicting snow accumulation and ablation is critically important for managing California's finite water resource.

Mountain snow accumulation and persistence are affected by many factors including elevation, aspect, degree of sheltering from wind and canopy cover (Marks and Winstral, 2001; Bales et al., 2006; Rice et al., 2011). Elevation plays a large role in snow deposition in the Sierra Nevada, with snow depths observed to increase approximately 15 cm per 100 m elevation in one spatially extensive measurement (Kirchner, 2013). Based on reconstructing snow accumulation from satellite snowcover and snowmelt estimates, Rice et al., (2011) found that the middle elevations (2100-3000 m) of the Merced and Tuolumne Basins contributed approximately 40-60% of the total snowmelt, and that the lower snow-covered elevations (1500-2100 m) contributed only about 10-15% of the total annual snowmelt. These low-elevation regions showed a high level of variability in snow accumulation and melt volumes and will be most affected by warming temperatures. The historical index of the water-year snow loading, the April 1 SWE measurement, was found, for most snow courses in the Western United States, to correlate well with climate trends, and that snow course's located at relatively low elevations were particularly vulnerable to increases in temperature (Mote, 2006). The last 20 years have proven to be the warmest years in the historical record, and projections indicate that the Sierra Nevada will continue warming; however analysis of historical data also shows that precipitation trends have not shifted (Diffenbaugh et al., 2015). Lower-elevation forests, located at or below the rain-snow transition zone, are particularly susceptible to increases to temperature and are at risk of having negligible snowpack in the future.

In addition to elevation's effects on snow accumulation and ablation, aspect has a pronounced effect on both snow deposition and melt. When examining snowfall on a large scale, snow deposition is with regard to aspect is mostly dominated by climactic variables. For example, in the Sierra Nevada storms typically come from the west and deposit more snow in the western versus the eastern slopes due to the properties of orographic precipitation and the rainshadow effect. When examining aspect's role on snow deposition at a relatively small scale, snow deposition becomes more a function of local topography and wind (Elder et al., 1991). While the windward side of a slope may receive more snow deposition due to it being the direction of the incoming storm event, wind redistribution will move snow from the windward side of the slope to the leeward side due to the sheltering effect of the slope (Winstral et al., 2002). Local topography affects snow deposition by dictating the amount of wind redistribution that will occur. Snowmelt rates are also affected by which aspect the snow pack lies on. In the northern hemisphere, more solar radiation is received on the southern and western aspects than the northern and eastern aspects. This increase in insolation leads to increased ablation rates on the southern and western aspects and reduces snow pack persistence (Pomeroy et al., 2003; Erxleben et al., 2002).

The effects of forests and vegetation on snow cover has been widely researched and many reports indicate that there can be fairly significant differences in snow deposition and ablation over relatively small spatial distances (Kittredge, 1953; Link and Marks, 1999; Marks and Winstral, 2001; Kirchner, 2013). Snow-cover deposition and ablation rates have been shown to be sensitive to vegetation structure (Hardy et al., 1997; Link and Marks, 1999). When snow falls in a forest, a substantial quantity can be intercepted by the forest canopy (Musselman et al., 2008). In the Boreal forest, up to 60% of the annual snowfall can be intercepted, with approximately 50% of that intercepted snowfall sublimating back to the atmosphere (Pomeroy and Schmidt, 1993). Storck et al., (2002) found that between 72 and 28% of the snow intercepted by the forest canopy either sublimates or evaporates off and never reaches the forest floor in the Umqua National Forest in Oregon. More snowpack accumulates in small forest gaps than underneath the canopy due to interception, and both denser canopy and higher leaf area index can be correlated to reduced snow accumulation (Golding and Swanson, 1986;

Link and Marks, 1999; Pomeroy et al., 2002; Musselman et al., 2008; Kirchner, 2013). Kattelmann et al., (1983) observed that different kinds of forests at different elevations required different sizes and shapes of forest gaps to maximize snowpack loading. While these forest gaps accumulate more snow, it has been shown that ablation rates in open areas, not covered by the forest canopy, can be 25-50% higher than ablation rates underneath forest cover (Link and Marks, 1999; Storck et al., 2002; Musselman et al., 2008; Veatch et al., 2009). Higher melt rates in the open are typical, especially in low temperatures, where most of the energy input is coming from shortwave solar radiation; however when ambient air temperatures are well above freezing, melt rates are higher underneath canopy cover (Lopez-Moreno and Latron, 2008).

The overhead forest canopy, as well as intercepting precipitation, reduces the amount of incoming shortwave radiation, emits longwave radiation, and shelters the snowpack from wind (Musselman et al., 2008; Pomeroy et al., 2009). The density of the overhead canopy limits the amount of incoming shortwave radiation; and as the solar angle increases through the spring ablation period, longwave irradiation increases, however canopy density or closure does not meaningfully impact the amount of longwave radiation emitted from the canopy (Pomeroy et al., 2009). Forest cover can also affect snow surface albedo by deposition of organic matter onto the snow surface, and therefore increase the energy input into the snowpack (Hardy et al., 2000). Pomeroy et al., (2009) described the extent to which tree trunks emitted higher amounts of longwave radiation than the overhead canopy.

It has been shown that removal of vegetation from a landscape increases snowpack and overall water yield; and therefore, mechanical forest thinning leads to increased snow accumulation (Bales et al., 2011). A paired watershed study in the Idaho Rockies showed that approximately three times the amount of snow accumulated in a clearcut and twice as much in an area with 50% basal area removed than in an undisturbed forest. It was also found that the clearcut and thinned areas of the forest retained snow cover longer than did the undisturbed forest (Hubbart et al., 2015). The Coon Creek watershed study located in Wyoming showed that a clustering of small group selections within a large watershed could significantly increase the water yield from the basin (Troendle et al., 2001). Troendle et al., 1985 showed that even thirty years post treatment, a watershed that had clearcut treatments still exhibited increased snowpack and water yield on an annual basis. To focus more on the Sierra Nevada, Anderson et al., (1976) recorded increases of maximum snow depth ranging between 19-34% between multiple types of forest treatments, ranging from group selection to clearcutting and stripcutting. Kittredge (1953) found that more snow accumulated in the forest gaps and large clearings than under forest canopy, and depending on the year and amount of snow deposited, the clearings and sparser forests held snow on the ground longer. Kattelmann et al., (1983) discussed the use of different thinning treatments for different forest types and elevations to maximize snow deposition and maintain snowpack persistence for longer into the summer. In addition to greater snowpack accumulation and increased snowpack persistence, Bales et al., (2011) estimated that the reduction of 30% of the canopy cover from a mid-elevation fir-dominated forest could potentially increase water yield by up to 16% and delay snowmelt by days or weeks.

Due to the past 110 years of fire suppression, much of the Sierra Nevada forests are much denser and more prone to high-intensity wildfires than ever before (Agee and Skinner, 2005). The principal vegetation communities have shifted from predominantly large-diameter trees to dense stands of small-diameter trees where larger trees have been removed by logging (Bouldin, 1999). The stand structure of the white-fir mixed-conifer forests were historically comprised of heterogeneous patches of differing sizes and of varying density interspersed with forest gaps, but are now comprised of more homogenous stands with less diversity in species composition and little to no forest gaps (Fites-Kaufman et al., 2007; Lydersen et al., 2013). These Sierran forests are now densely packed stands with heavy surface fuel loads and small trees that act as ladder fuels, allowing what would have historically been a low to moderate intensity wildfires to move up into the crowns of the forest overstory and transform into stand-replacing, high-intensity wildfires. Large, high-intensity wildfires remove all dominant vegetation structure and allows for a completely new forest type to initiate and move into the area and in some cases take decades to centuries to return back to the same type of forest structure that was there before (Dore et al., 2012). In addition to a forest type conversion, by-products of high-intensity wildfires hydrophobic effects on the soil creating increased runoff and increased sediment loading into local streams and rivers, decreased air quality and the release of enormous amounts of green-house gasses into the atmosphere, and loss of local wildlife habitat (Dore et al., 2012; Lydersen et al., 2014; Gonzales et al., 2015).

New research suggests innovative ways of managing Sierra Nevada forests which introduces varying densities of forest stocking based on variables such as aspect, slope and elevation in an attempt to restore the Sierra Nevada mixed conifer forests back tree densities and spatial arrangements witnessed before widespread logging and fire suppression (North et al., 2009). Management strategies presented in the Pacific Southwest Research Station General Technical Report (PSW-GTR) 220 theoretically will provide healthier, more wildfire and drought resilient sierra mixed conifer forestland by creating more diversity in both species composition and forest structure and should create more diverse habitat types for wildlife. Previous to the publication of PSW-GTR 220, foresters would create evenly spaced forest stands in the hope that this would best allocate water and nutrients to the growing trees and provide the best chance of minimizing crown-fire spread. The management strategies presented in the PSW-GTR 220 also recommend a regular introduction of controlled burning back to the landscape. This practice of regular burning will help alleviate the likelihood of future high-intensity wildfires from completely removing all of the vegetation (Agee and Skinner, 2005; North et al., 2009; Stephens et al., 2009). While the conventional forest management strategy meets the goals of the land managers, the new forest strategies off to bring a higher level of heterogeneity to the forests that would have historically been present.

` There is no question against the acute need in the Sierra Nevada for forest management to reduce the risk of high-intensity wildfire, maintain and preserve our mountain snowpack, and return the Sierra Nevada forests back to pre-logging and fire suppression levels. By conducting snow surveys and deploying snow depth sensors to quantify snow accumulation as well as deploying a distributed network of temperature loggers on the forest floor to capture melt-out date, we set out to determine if there was any difference in snowpack accumulation or ablation rates between new the management strategies presented in the PSW-GTR 220 and conventional forest thinning techniques.

Our hypothesis was that the new variable density thinning with the inclusion of forest gaps would accumulate more snow than the conventional, even spacing thinning technique, due to the canopy being more open. Due to results from Lundquist et al., (2013) where it was discovered that at lower elevation, warmer sites, the snowpack persisted longer in the open than under the forest canopy, and studies like Kittredge (1953), it was also hypothesized that the new variable density thinning structure would exhibit greater snowpack persistence than the conventional thinning pattern. Also, Kattelmann et al., (1983) described the best way to manage the Sierra mixed conifer forests for increased snowpack and snow persistence was to incorporate small forest gaps of less than 0.5 ha with shape and size depending on aspect and slope. Literature published in the central Sierra and around the western U.S. all support the need for greater canopy openness and forest gaps as the most effective way to accumulate more snow and allow it to persist longer into the season.

Methods

We examined snow-distribution patterns between two forest thinning treatments plus a control across 24 plots in the Stanislaus-Tuolumne Experimental Forest. Treatments, carried out in the summer of 2011, consisted of two different forest thinnings where similar quantities of biomass were mechanically removed, however the remaining trees were left in uniform versus variable spatial patterns. A combination of manual snow surveys and continuous snow sensory equipment was used to quantify snow accumulation and ablation between the forest treatments and control.

Study site

The study took place within the Variable Density Thinning Study (VDTS) in the Stanislaus-Tuolumne Experimental Forest (STEF) located in the Stanislaus National Forest near Pinecrest, CA (Figure 1a). The study site lies on the northern edge of the Tuolumne basin, and ranges in elevation from approximately 1760 to 1820 m. Its climate regime is characteristic of the Sierra Nevada, having a cool wet winter and a warm dry summer. In an average year, the site receives approximately 100 cm of precipitation, with a majority being deposited between December and March and nearly half falling as snow (Adams et al., 2004). Average temperature range for January is -7 to 7 ˚C and approximately 6 to 27 ˚C for July (Adams et al., 2004). The majority of the soils are moderately deep, rocky, well-drained sandy loams of the Wintoner-Inville complex. The dominant vegetation is a typical Sierra mixed-conifer, consisting predominantly of white fir (*Abies concolor)*, incense cedar (*Calocedrus deccurens)*, ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyi*), sugar pine *(Pinus lambertiana*), and small amounts of California black oak (*Quercus kellogii*). Shrub species, including greenleaf manzanita (*Arctostaphylos patula*), bearclover (*Chamaebatia foliosa*), and a variety of ceanothus (*Ceanothus cordulatus, C. intergerrimus, C. parvifolius*) are also abundant.

The VDTS was installed on 240 acres on the STEF that has been devoid of major forest disturbance for approximately 90 years. This particular area has not had a natural wildfire since 1889, through the natural fire-return interval for this type of Sierra mixed-conifer forest is typically 5-8 years (Knapp et al., 2013). Thus this particular forest is between 15-22 cycles of fire behind what would naturally have occurred here prior to the loss of ignitions from the Native Americans and the fire suppression policies of the U.S. Forest Service. It is also good to note that the last time the site was mechanically logged was in the 1920's, and has not had any mechanical treatment since. During the past 90 years this forestland has grown to be very dense and full of small-diameter trees. It is also noteworthy that the species composition has shifted more towards a white-fir and incense-cedar dominated forest and contains a smaller fraction of pines than were seen in the 1920's (Knapp et al., 2012 and Knapp et al., 2013).

`The VDTS created three forest treatments replicated eight times within 24, approximately 4-ha, units (Figure 1b). The treatments were a high-variability thinning, a low-variability thinning, and an unthinned control (henceforth called variable, even, and control). Both forest-thinning treatments were intended remove approximately the same

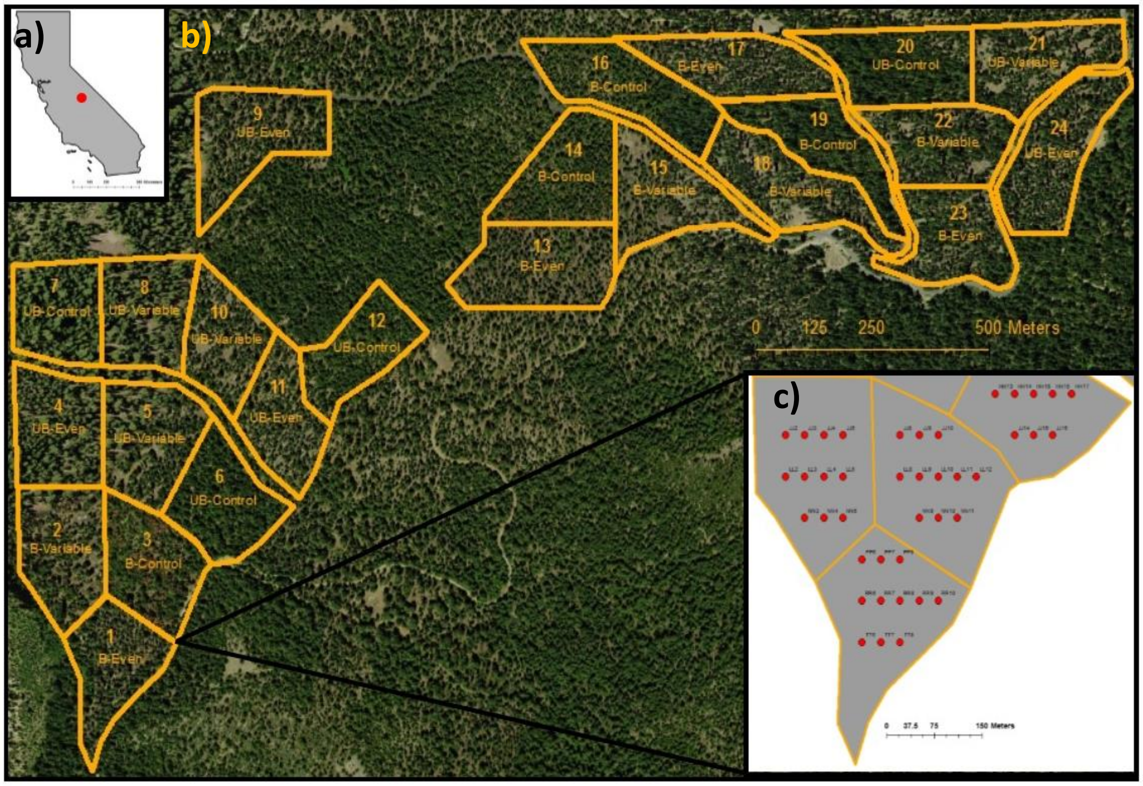

Figure 1. Panel a shows the study sites relative location in the Stanislaus-Tuolumne Experimental Forest within the Stanislaus National Forest. Panel b is a map of study site showing all 24 4-ha units and their associated forest treatments. Panel c shows distribution of measurement points within a few of the treatment units.

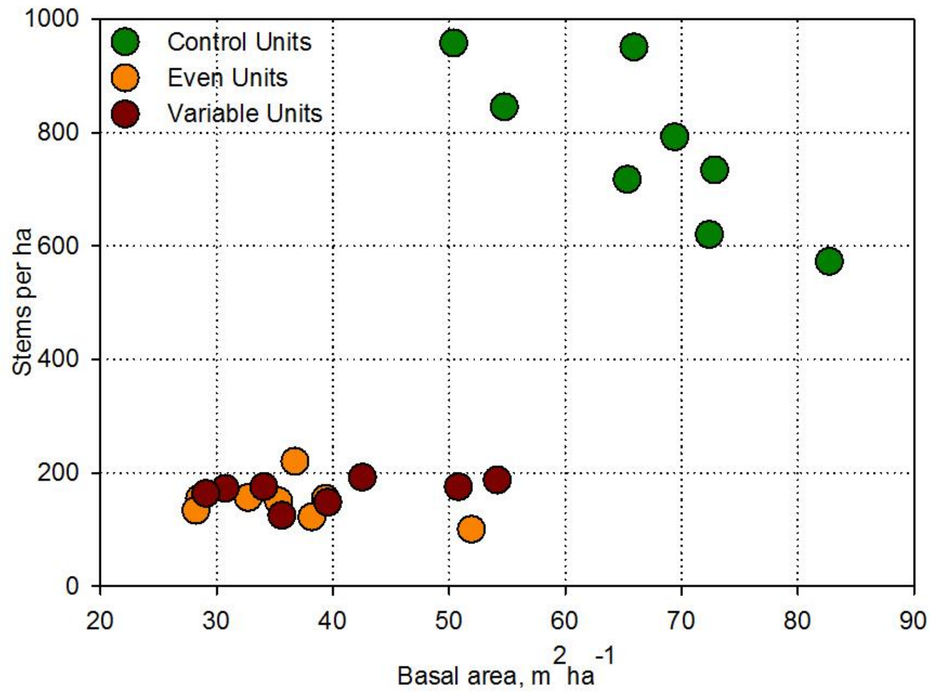

Figure 2. Illustrates the stand metrics found within the study site. Each point represents a treatment unit. It becomes apparent that while the treated stands were all reduced to a very similar density in way of stems-per-ha, there is quite a disparity in way of basal area between the units.

amount of biomass from the units and reduced stems-per-ha by 80% and basal area by 40% (see Figure 2b), the main difference between these treatments was the spatial configuration of the residual trees. The even treatments left all residual trees with as even as spacing as possible, with no intentional canopy gaps. Although gaps do occur, they are on the scale of meters, whereas the gaps within the variable units are on the scale of tens of meters and were prescribed to range between 0.1 and 0.5 acres in size. The even treatment approximated the current standard for forest thinning in the Sierra, where crowns of individual trees are spaced from each other to reduce crown-fire spread. Even spacing also allows the trees to theoretically maximize the amount of water and nutrients in the immediate root zone. The variable treatment was designed to restore forest densities and stand structure closer to historical levels found before widespread logging and fire-suppression efforts in the Sierra, and was based on stem-maps developed in unlogged old-growth stands at STEF in 1929 when US Forest Service employees were prepping for the "Methods of Cutting" study (Knapp et al., 2012). These variable units are comprised of small 0.1-0.5 acre gaps (five per each 4 ha unit) intermixed with groups of trees of varying density to create a heterogeneous landscape pattern with breaks in the canopy fuel loading. The variable treatments were also aimed at generating a greater diversity of wildlife habitat with the forest clumps and gaps. Thinning operations within the project were executed in the summer of 2011.

A total of 251 permanent measurement points were established by the US Forest Service in the summer of 2012. To create these points a 30 * 30 m grid was overlaid over the entire study site, oriented in the cardinal directions. Rows in the north-south directions were labeled with alphabetic characters and columns in the east-west direction were labeled with numeric characters to give each point a specific alphanumeric identification code. Within each unit there was 240-m of transect line installed, divided between 2-3 transects running in the east-west direction across 3-6 of these grid points. This is how the 10-11 permanent measurement points per treatment unit was created. The transects within the units are space 60-m apart in the north-south direction so that sampling within the units is more distributed throughout, and are intended to be located within the centermost region of the treatments to avoid edge effects from adjacent treatment units (Figure 1c).

All measurement points were marked with a piece of rebar hammered into the ground so that approximately 30-cm of the rebar is above the forest floor. All rebar point markers were topped with a metal cap engraved with the particular measurement point's alpha-numeric identification code. In addition, every measurement point was flagged with a combination of orange and blue flagging around a nearby tree and hanging as close to directly over the point as possible to make locating the points easier. A 2-m bamboo stake was also attached to the rebar at the ends of each transect and every other measurement point within the transect, specifically to make them more visible during the snow surveys. Each bamboo stake was fitted with bright orange and blue flagging as well to increase visibility.

One half of the treatment units were prescribed a low-intensity burn. The prescribed burn took place in November of 2013, as all earlier attempts at burning were postponed due to weather. The prescribed burn took approximately 5 days to complete. As burning conditions were not optimal, complete burning of understory and surface fuels took longer than anticipated and crews were able to complete 2-3 treatment units per day. After burning operations all bamboo poles and flagging were returned to previous locations to mark ends of measurement transects.

Meteorological stations and snow-depth sensors

In February of 2012, two 6-m meteorological towers were erected at opposite ends of the project to capture the elevational extremes (1760-1820 m) within the project boundary. Towers were set inside variable units 8 and 21 (opposite ends of the project) inside some of the larger gaps created by the treatments (Figure 3). This placement also helped to ensure proper illumination for a solar panel to run the instruments. These particular units were chosen to host the meteorological towers as they were not prescribed for low-intensity burning. Each tower was equipped with a Campbell Scientific CR-1000 datalogger, a Campbell HMP45 temperature and relative humidity sensor placed approximately 2-m high, a LI-COR LI-200 pyranometer placed on the south side of the tower and at a height of approximately 3 m. A TE525L tipping bucket was installed at the top of the tower at an approximate height of 6 m, and a 1.5 m horizontal cross arm was installed at a height of approximately 5.5 m and holds both an R.M. Young anemometer and wind vane set. In April of 2013, after the snowmelt, both towers were equipped with two CS 650L Soil Water Content Reflectometers placed at depths of 10 and 30 cm. In November of 2013, each tower was equipped with a CS SR50 sonic rangefinder, installed at a height of approximately 2.75 m to capture snow depth. All sensors were tested and calibrated according to their user manuals prescription prior to being deployed, and were calibrated in the field in the summer of 2014. These sensors recorded hourly data without break since February 2013. Hourly data from these instruments was converted to average daily readings for some sensors like the pyranometer because of such high daily fluctuations. Data from tipping buckets was summed by day and year to show annual accumulated precipitation. Annual precipitation amounts were summed and recorded by water year (October 1st through September 30th) which is standard reporting procedure utilized by California Department of Water Resources and many other water agencies.

In February of 2014 a total of ten snow-depth sensor nodes were installed in two clusters around the two meteorological towers (Figure 3). These nodes consisted of a Judd ultrasonic depth sensor mounted at the end of a 1.2-m cross-arm mounted on top of a 4.8-m pole, and a Sensirion SHT1x temperature and relative humidity sensor located on the same cross arm recording 15-minute data to a Metronome Systems Neomote wireless datalogger. The sensor arrays were set up at specific measurement points within the variable units that contain the meteorological towers and adjacent control units. Four snow-depth nodes were clustered around each meteorological tower, distributed to capture snow accumulation and ablation under three different canopy classes within the variable treatments (under canopy, drip-line, and open). The final two snow-depth nodes were set in adjacent control units (units 7 and 20), to capture additional canopy conditions potentially influencing snow loading in the project site.

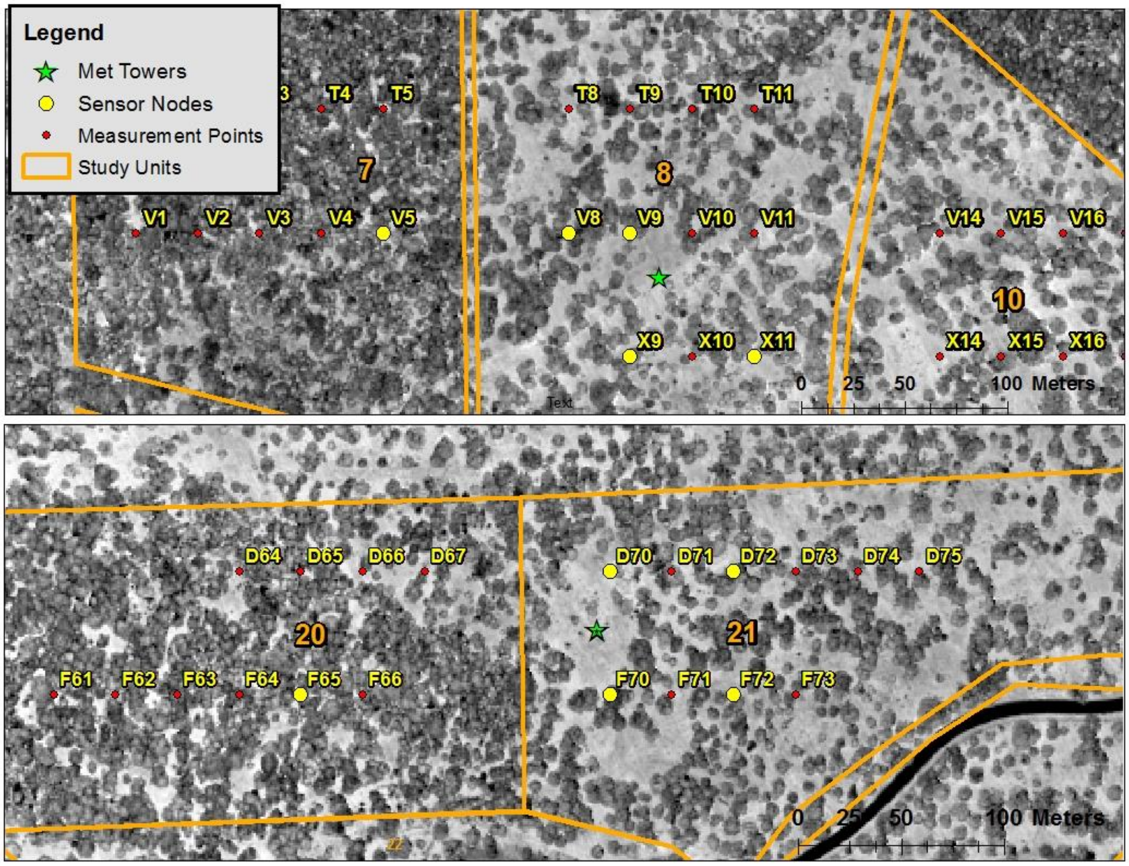

Figure 3. Depicting locations of meteorological towers and snow sensory nodes.

Snow surveys

Snow-survey timing was initially planned to consist of a primary survey capturing peak snow accumulation, followed by subsequent surveys every two weeks to capture the ablation period. Snow surveys were completed on March 7, 21, and April 2, 2013 and April 1, 2014 with the March 7, 2013 and the April 1, 2014 survey representing our peak-accumulation surveys. No survey was completed in 2015 on account of the minimal snowpack.

Snow surveys were conducted by teams of two to four individuals carrying a minimum of a compass, handheld Magellan GPS and 3-m aluminum avalanche pole. Survey crews made their way to all 251 measurement points and took five snow-depth measurements using the avalanche pole. Depth measurements were made at the point center and at approximately 3 m from point center in the cardinal directions to collect five subsamples from each measurement point. In addition to collecting depth data, a canopy observation was made looking straight up from point center to determine if the measurement point lay under the forest canopy, at the drip edge of the canopy or out in the open. All data were recorded digitally with a handheld Magellan GPS. Snow-survey crews took special precautions to disturb the snowpack as little as possible by only allowing one individual to walk within 6 m of the measurement point to measure depth, while the other member of the group recorded data. Care was also taken to not snowshoe within the measurement transects, not only for the fidelity of future snow surveys, but to ensure that the snowpack goes through a completely natural ablation period so as not to adversely affect underlying forest vegetation and ultimately affect collaborative research efforts also using the VDTS.

For every snow survey, snow density was measured by digging snow pits and weighing samples of snow with a known volume. Between two to three snow pits were dug at the time of each survey depending on the snow depth and relative quality of weighed samples used from the pits. A suitable location, preferably the deepest local snowpack, was found in the forest gaps near each of the two meteorological towers and a 1-m minimum width snow pit was dug with a snow shovel. The measurement face was edged and cleared of any debris before using a 1000-cm^3 cutter to sample snow density at every 10-cm depth as following the methods utilized in Rice & Bales, (2010). Snow samples of known volume were only weighed and recorded if they met a quality check where they were free of any foreign material or void space, thus obstructing the true weight of the sample. Samples were weighed with a digital field scale and recorded to the tenth of a gram. All snow samples from an individual pit were integrated to capture the average snow density so that a calculation of snow water equivalent (SWE) could be made for the survey. SWE values for the survey points were calculated by multiplying the average measured depth by the average density found between the two snow pits.

Distributed light and temperature loggers

A total of 251 HOBO pendant 64-bit temperature and light loggers were deployed along the forest floor to capture snow melt-out date for every measurement point. All loggers were secured to the forest floor between 1-2-m south of the measurement point. The sensors were placed far enough away from the measurement point that sensor readings and snow melt out were not affected by the metal measurement-point marker, and close enough to ensure that the pendant sensor was placed under the same canopy class as the associated measurement point. Loggers were secured under approximately 2-5 cm of forest litter so that the logger itself did not affect snowmelt and that the sensor casing would avoid direct sunlight. Each pendant logger was set to record temperature and light intensity hourly, and when temperature stayed static at approximately 0-1 ˚C for longer than 3 days, it was assumed that there was snow cover over the logger. Likewise, once diurnal fluctuations in temperature were noticed again it was considered the day of melt-out. In addition to the day that the logger experienced meltout, we calculated melt-rate by dividing the maximum recorded snow depth by number of days it took until complete meltout. Loggers were deployed in the fall or summer of 2012, 2013, and 2014, and were retrieved the following summer for data download and battery exchange.

Hemispherical-photographs

In the summer and fall of 2012, hemispherical photographs were taken of the overhead canopy at every measurement point. Photographs were taken using a Nikon D3000 with a Sigma 4.5-mm 1:2:8 fisheye lens which provided a 164˚ view of the forest canopy. All photographs were taken using a leveling tripod with the camera facing straight up at the canopy and the top of the camera facing north. For each photograph the camera tripod was set exactly over the metal point marker cap and set so the camera was at a height of 1.5 m. All photographs were taken in early morning or evening when the forest was illuminated with diffuse light.

Photographs were analyzed using freeware Gap Light Analyzer (GLA) 2.0 and R packages "readbitmap" and "reshape2." First, using GLA, and following recommended settings from Frazer et al., (1999), hemispherical photographs were converted to binary bitmaps that showed distinction between canopy and sky (Figure 4a). Zenith angle locations on the photos were determined following the same protocols as Musselman et al., (2012), by counting the number of pixels from the center of each photograph (nadir) to the edge, then dividing that pixel count by the radial range of the photograph, 82 degrees. From there, concentric circles were drawn through each photograph at every other zenith angle, and the ratio of canopy to sky was calculated for each of these 41 iterations (Figure 4b). To find which zenith angle that correlated best to maximum snow depth we ran a linear correlation between sky-view fractions calculated for all zenith angles computed and maximum snow depth recorded on our maximum accumulation surveys in the springs of 2013 and 2014. Sky-view fraction data utilizing the optimal zenith angle was also used to calculate canopy-closure.

LiDAR data

In the fall of 2014, the NASA Jet Propulsion Laboratory (JPL) collected 1-m resolution LiDAR data from the STEF. NASA JPL error checked, cleaned the data and provided ground surface and high-hit raster datasets in the spring of 2015. In order to get an estimate of canopy-cover as opposed to canopy-closure as documented in Jennings et al., (1999), the ground surface dataset was subtracted from the high-hit to produce a binary map that displayed areas with canopy-cover and areas of bare earth. This analysis was completed using ArcMap 10.2.1.

Statistical analysis

Statistical analysis was completed using R statistical software version 3.1.0. Significant differences were accepted at $p<0.05$. Differences in means were evaluated using a combination of ANOVA, a Welch Two Sample t-test, and Tukey's (honest significant difference) HSD to determine which of the three treatments and canopy classes differed from the other two. Linear regression was used to find the maximum R^2 value between sky-view fraction and maximum snow depth to find optimal zenith angle to use when processing the hemispherical photos. Data gaps caused by sensor malfunction or obstruction of sensor capture-zone in continuous snow-depth sensor measurements were filled using a 1-to-1 linear-regression interpolation between sensors that maintained data continuity throughout gap-filling period.

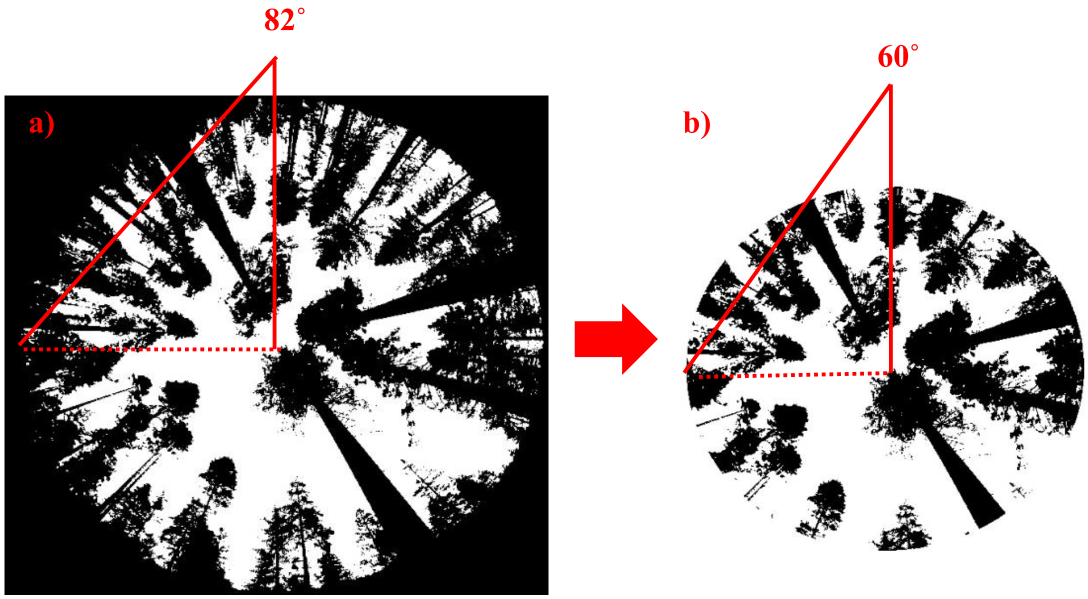

Figure 4. Hemispherical photographs were analyzed for sky-view fraction for every other zenith angle ranging from the edge of the photograph, 82˚, to 2˚ from nadir.

Results

Meteorological conditions

Data from the two meteorological towers located at the elevational extremes indicated similar values for all variables measured except for air temperature. On average the lower elevation tower (1760 m) reported 0.5 C warmer than the upper elevation tower (1820 m). Average winter air temperature were measured at 3, 4.3, and 4.7˚ C for 2013, 2014 and 2015 respectively (December 21-March 21). Average daily windspeed was 0.5 m s^{-1} and typically blew in from the southwest. Total accumulated precipitation measured from tipping buckets were approximately 800 and 600 mm for water years 2013 and 2014. The total accumulated precipitation measured until mid-May for water year 2015 was 550 mm. Daily average solar radiation was measured at 250 W m^{-2} in June and 30 W m^{-2} in December.

Snow surveys

The maximum-accumulation snow survey of 2013 occurred the day after the last large snowstorm of the season (Figure 5). The mean snow depth for the whole study site was 39.6 cm, and had an average snow density of 451 kg m^{-3}. The variable, even, and control units reported mean snow depths of 43.5, 40.9, and 34.6 cm respectively (Figure 6a). The snow depth recorded within the one-way ANOVA testing show that these treatments have different means in snow depth ($p<0.05$), and it was found that there were not statistically significant differences between the variable and even units ($p=0.37$), indicating that the variable and even units accumulated approximately between 20 and 15% more snowpack than the control units respectively.

The April 1, 2014 maximum-accumulation survey was also completed on the day following one of the largest snowstorms of the season, and prior to this snowstorm the site was free of any snowcover (Figure 5). The mean snow depth recorded for the site was 35.2 cm and an average snow density of 180 kg m^3. In the autumn before this survey, half of the study site experienced a low-intensity prescribed fire, however this prescribed fire made no impact on the accumulated snow depth ($p = 0.19$). Mean snow depths of 36.2, 36.7, and 32.7 cm were recorded for the variable even and control, respectively (Figure 6c). It was found that the control units accumulated approximately 10% less snow depth than the two treated units ($p<0.05$). A Welch two-sample t-test shows that the variable and even units did not have separate means ($p = 0.30$), and that the 2% greater snow depth recorded in the even treatment was not statistically significant.

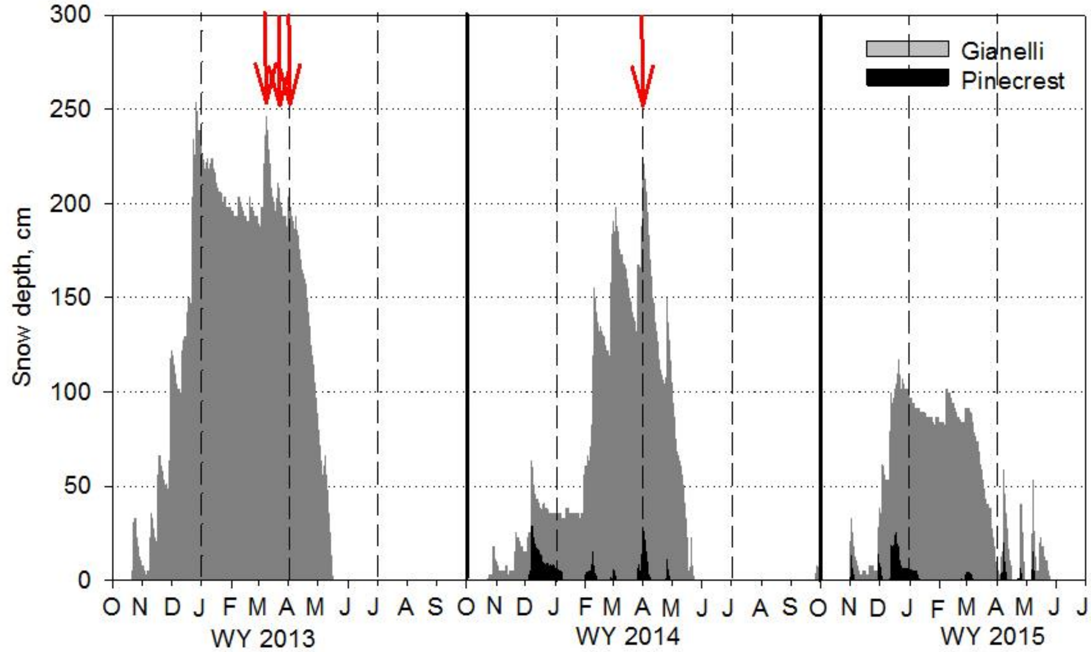

Figure 5. Depicts timing of snow surveys with red arrows. Maximum accumulation snow surveys for WY 2013 and 2014 were conducted the day after large snowstorms. The shaded grey area indicates the Gianelli Meadows snow-depth sensor data, the black shaded area depicts snow depth recorded at the project site from multiple snow sensors placed in differing canopy coverages. Gianelli Meadow data is used here because on-site snow sensors were not installed in the project site until November of 2013.

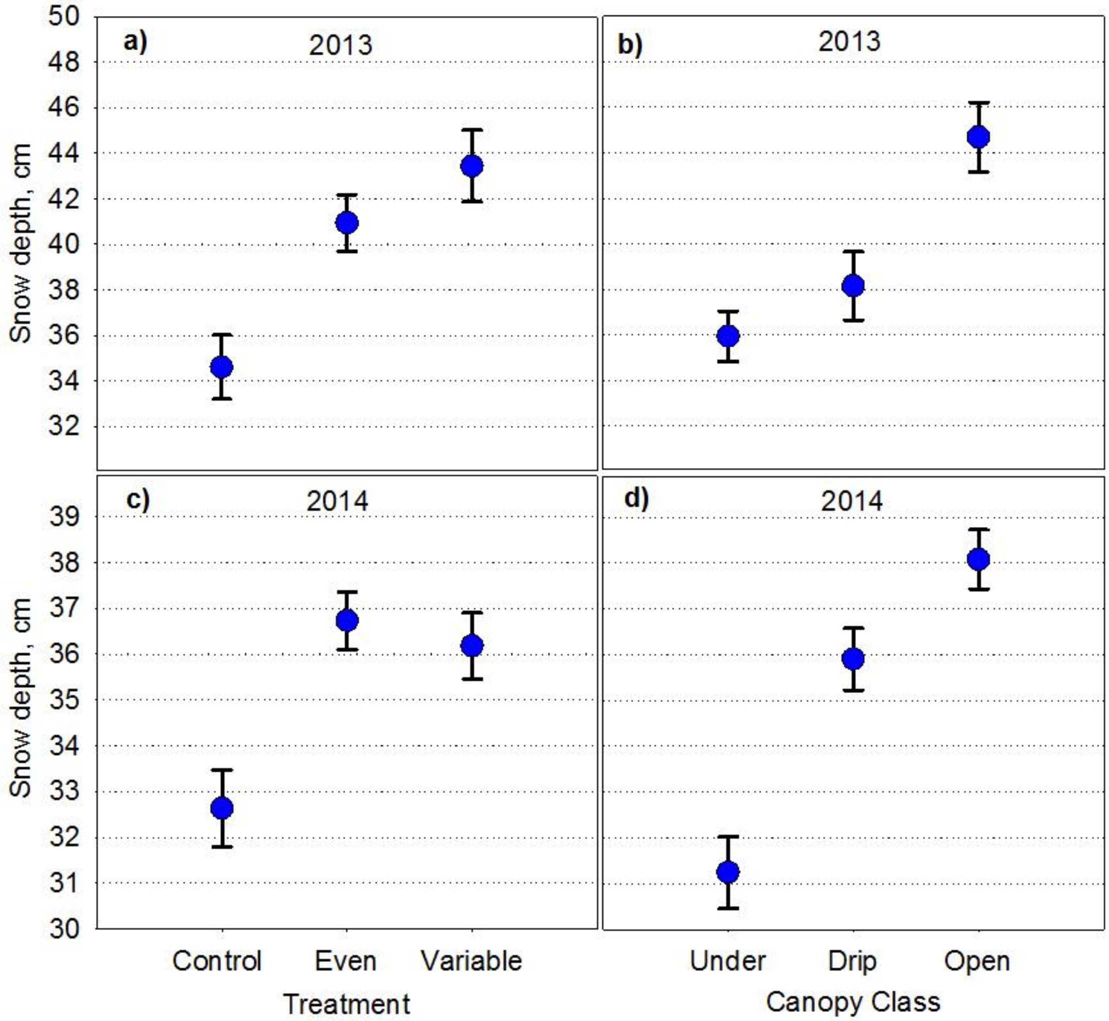

Figure 6. Results from the two maximum-accumulation snow surveys. These plots show the mean and the standard error of measured snow depth between the three forest treatments and canopy classes. Panels a and b show results from the March 7, 2013 survey and panel c and d show results from the April 1, 2014 survey.

Both peak-accumulation surveys in 2013 and 2014 showed significant differences in snow depth in relation to canopy class (Figures 6b & 6d). In the 2013 maximum-accumulation survey the open, drip-edge, and under-canopy classes had mean snow depths of 45.1, 38.8, and 34.6 cm respectively, and in the 2014 maximum accumulation survey the values were 38.0, 35.9, and 31.3 cm. In both water years the open class stood out as having significantly ($p<0.05$) greater snow depth, accumulating approximately 14% and 23% more snow than the drip-edge and under-canopy classes respectively, in the 2013 maximum-accumulation survey; and accumulated approximately 5% and 18% more snow in the 2014 maximum-accumulation survey. In fact, the snow depth measured at the open measurement points was statistically significant from the other two canopy classes within each of the three individual treatments for both years. The March 7, 2013 survey showed that open canopy class within the variable treatments accumulated more snow than the open canopy class for the other two treatments, accumulating approximately 12% more snow than the open class within the even units and approximately 21% more snow than the open class in the control units, however this trend was not found to be statistically significant ($p=0.09$). This trend was not seen in the 2014 maximum-accumulation survey, with the two thinned treatments' canopy classes showing approximately equal accumulation.

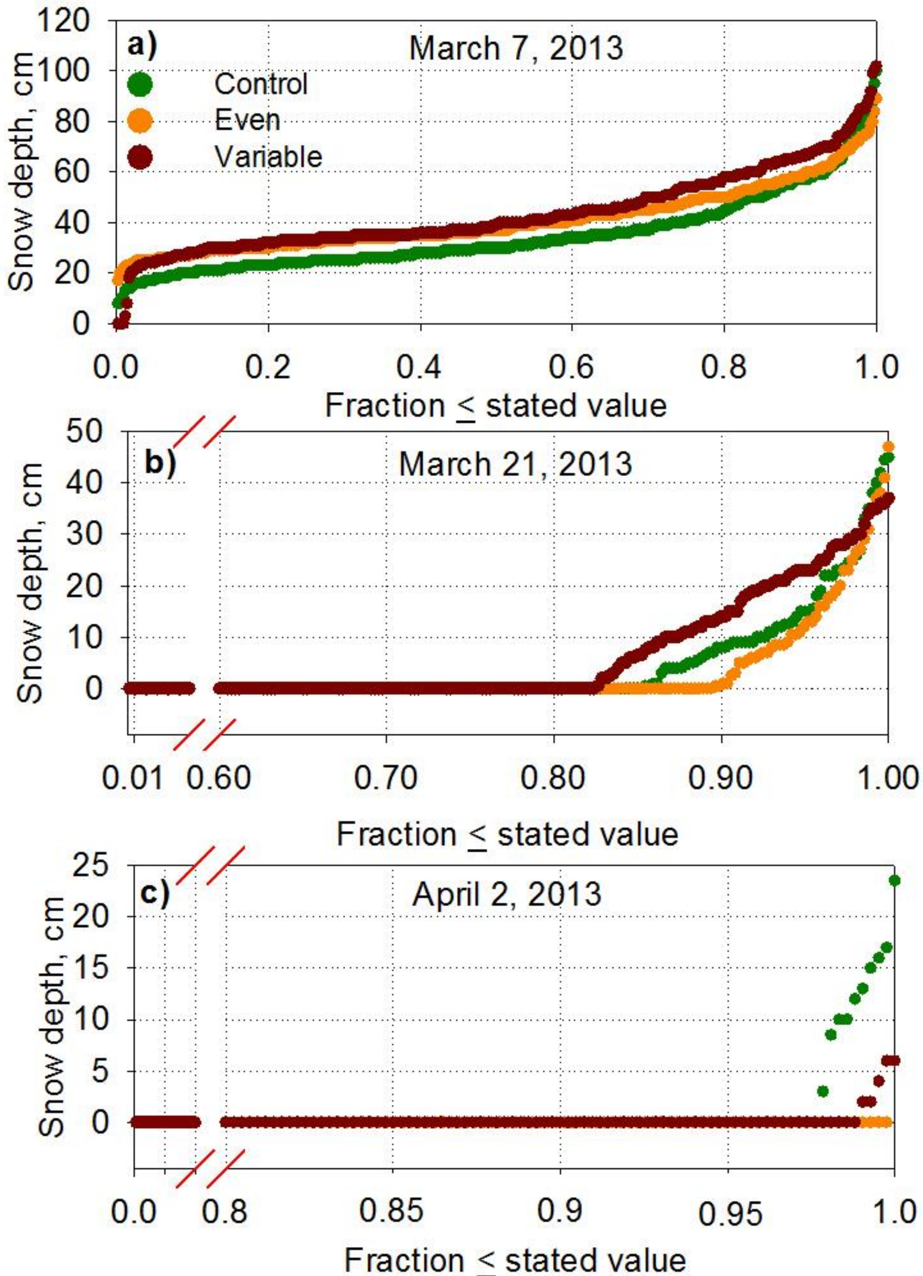

Figure 7. Snow survey results from 2013, distributed by snow-depth measurements in each forest treatment. These graphs show results of snow depth subsamples that give a better sense of the patchy snow cover witnessed in the latter surveys.

Results from subsequent surveys to quantify snow ablation were only available in 2013 due to there being a more-persistent snowpack. Also, the 2013 maximum-accumulation survey was earlier in the season when snowmelt rates were slower, as compared to the 2014 survey. The first 2013 survey showed that the average depth of the snowpack was approximately 39.6 cm, with a majority of the deeper snow measurements being found in the variable units, followed by the even and control units (Figure 7a). The second snow survey carried out two weeks later showed that approximately 75% of the 251 measurement points were snow free (Figure 7b). On March 21, 2013 there was an average of 2.3 cm of snow covering the study site as a whole, and however, the variable units retained more snow than the even and control units, approximately 47% and 31% more, respectively. Statistically, the control and variable units were indistinguishable from each other but did stand out as retaining more snow than the even treatments ($p<0.05$). Snow in the variable units was found primarily in forest gaps and in dense patches of trees.

By the April 2, 2013 survey, 94% of the measurement points were snow free (Figure 7c). Most of the remaining snow was found in the control units in under-canopy or drip-edge locations. The control treatment retained more snow than the variable treatment, which retained more snow than the even treatment, but differences were not statistically significant.

When grouping the measurement points out by aspect, it was found that aspect was significantly correlated with snow accumulation in the 2013, but not for the 2014 peak accumulation survey (Figure 8). The northeast aspect showed the greatest snow accumulation, and interestingly enough, the northeast was the only aspect that stood out statistically from the others. In 2014, no single aspect stood out statistically.

Snow survey results show that elevational differences in snow accumulation and persistence were found to be statistically significant (Figure 9). In 2013, the higher elevation half of the study site (units 13-24) had approximately 7.6 cm more snow than the lower elevation half (units 1-12) of the study site ($p<0.05$). The March 21 survey showed that there was approximately 3 cm more snow in the 12 higher elevation units ($p<0.05$). Due to the overall lack of snow on the April 2, 2013 survey, there was no statistical difference in snow depth as result of elevation. Results from the 2014 maximum accumulation survey show the 12 higher elevation sites accumulated approximately 1.3 cm more snow than the lower elevation units ($p=0.04$).

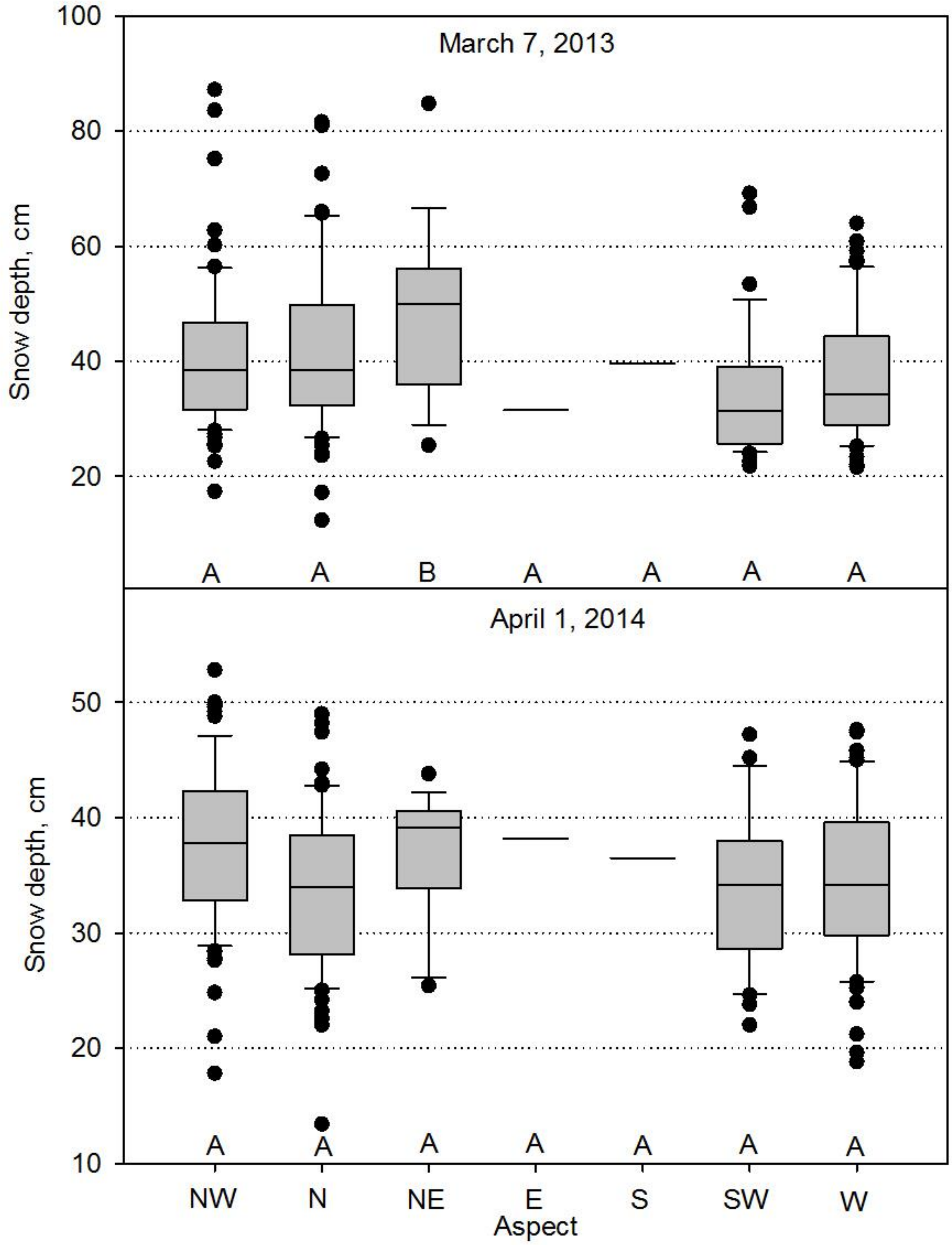

Figure 8. Maximum recorded snow depth by aspect. Letters indicate statistically significant differences.

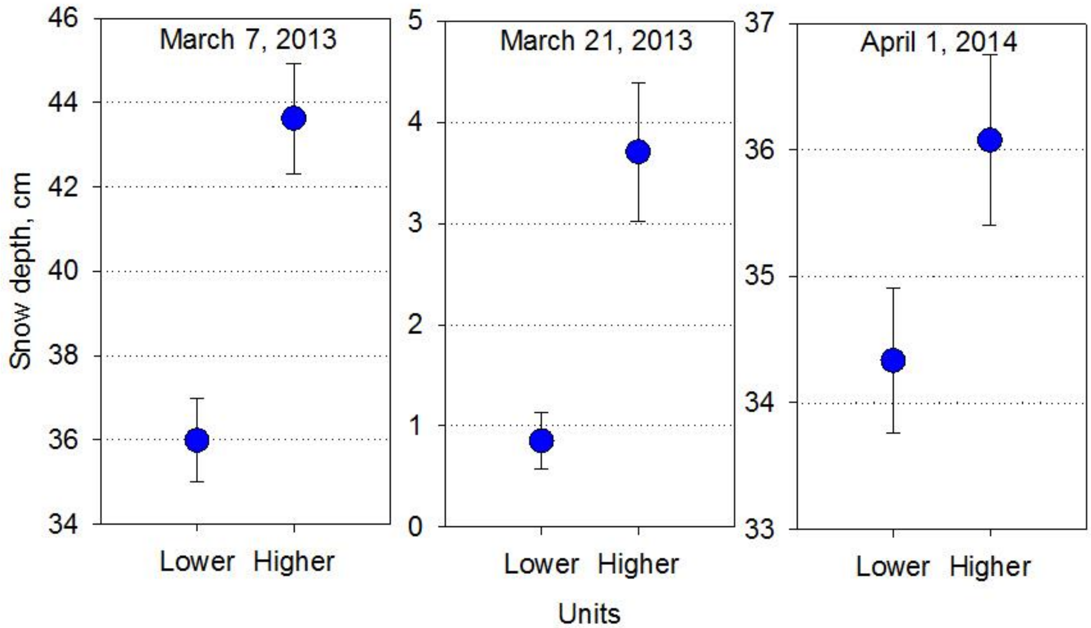

Figure 9. Depicts mean and standard error of recorded snow depth found between lower elevation units, units 1-12, and higher elevation units, units 13-24 for three of the four snow surveys.

Distributed temperature and light loggers

Results from the distributed temperature and light sensors show that a majority of the study site melted out between eight and nine days following the 2013 maximum-accumulation survey and approximately six days following the 2014 maximum-accumulation survey (Figure 10a & 10c). The average time until meltout for the control, even, and variable units in 2013 were 9.1, 8.4, and 9.3 days respectively, and in 2014 these were 6.6, 6.1, and 6.2 days respectively. In 2013 none of the treatments had a statistically significant difference in melt-out time after the maximum accumulation survey ($p=0.42$); however it was found that the 12 higher elevation units retained snowpack for approximately 3 days longer than the lower elevation units ($p<0.05$). In 2014, there was no significant signal that elevational differences within the study site had any effect on melt-out date. Sensor results did indicate that the two thinned treatments did not have significantly different melt-out times, however, the control treatment maintained its snowpack 7% longer than the two thinned treatments ($p=0.02$)

Melt rates, calculated from the distributed temperature and light sensors, showed that the two thinned treatments had faster melt-rates than the control treatments (Figure 10b & 10d). In 2013, the average melt-rates for the control, even and variable treatments were approximately 4.3, 5.3, and 5.3 cm day^{-1} respectively, and the two thinned treatments show indistinguishable melt rates, however the control treatment was shown to have an approximate 19% lower melt rate ($p<0.05$). In 2014 the average melt-rates for the control, even and variable treatments were approximately 5.4, 6.1, and 5.9 cm day^{-1}. In 2014, the even treatment stood out statistically from the other two as having an increased melt rate, approximately 8% faster ($p=0.02$). It was also found that the units that were prescribed a low-intensity burn showed no difference in melt rates than units that were not burned. Data from 2013 also show that snow in the open melted at approximately 0.78 cm day^{-1} faster than snow under the canopy ($p<0.05$). Snow in the open melted at an estimated rate of 5.35 cm day^{-1} and snow under the canopy melted at an estimated rate of 4.57 cm day^{-1}($p<0.05$). The canopy drip edge showed to be indistinguishable from either open or under canopy, and in 2014, no particular canopy class was indistinguishable from the rest with regard in estimated melt rate. In either year, estimated melt rates showed no signs of being affected by in-site elevational differences.

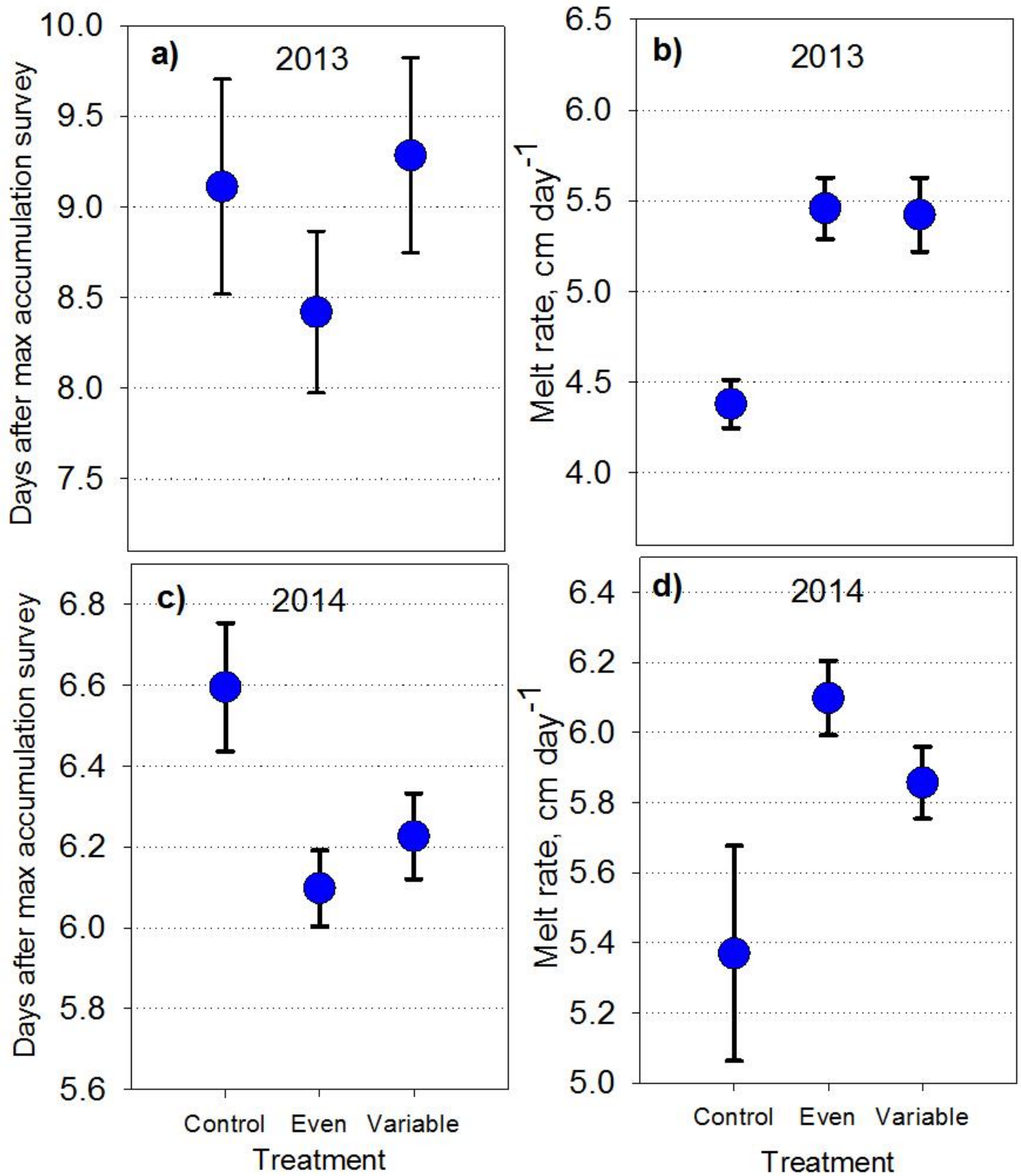

Figure 10. Data analyzed from calculated melt out date from distributed temperature/light sensors. Panels a and c represent average and standard error of days after peak accumulation that complete melt-out occurred for water years 2013 and 2014. Panels b and d represent calculated snow melt rate for water years 2013 and 2014.

Snow-depth sensors

Data from the 12 snow sensors show that melt rates and melt-out days for the three canopy classes were all very similar to each other for water years 2014 and 2015 (Figure 11). For every snowstorm recorded on the sensors, complete melt out occurred on the same or adjacent day. There was one instance in January 2015 with considerable differences in melt-out between the sensors placed under different canopy classes. The sensors recording the drip-edge class melted out first, followed by the open and under-canopy classes melting out five days later. Other noticeable differences in snowpack picked up by the sensors was that the open sites consistently accumulated the most snow, followed by the drip-edge and under-canopy classes for each storm recorded during the two years (Figure 11). Snow depth measurements captured by the distributed snow-depth sensors showed that the open canopy class accumulated up to approximately 52% more snow (9 cm) than the drip edge and up to (10 cm) approximately 62% more snow than under the canopy, but both the drip edge and under canopy classes had on an average of 20-40% less snow than in the open.

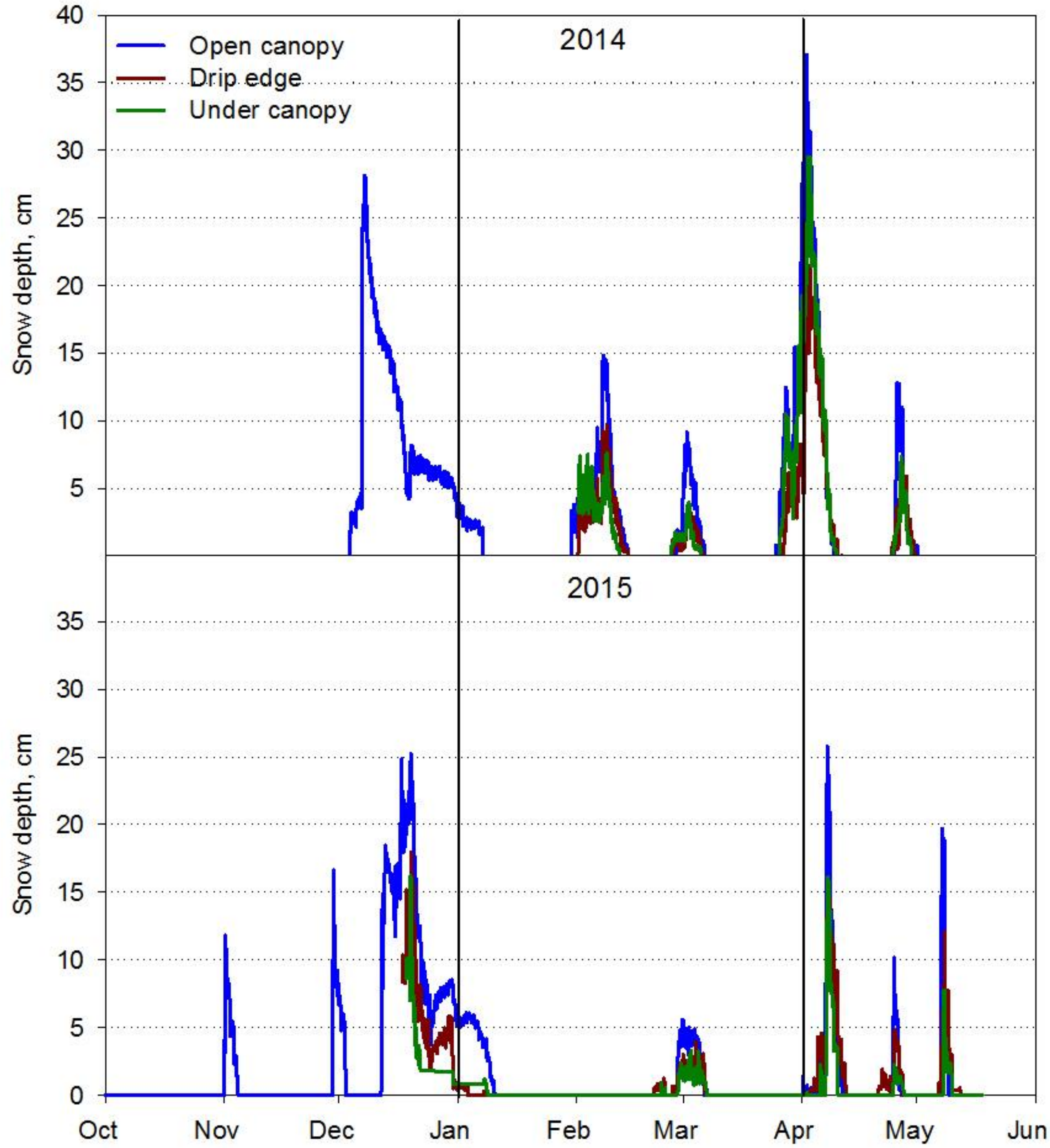

Figure 11. Depicting snow-depth sensor data parsed out by canopy cover class. The data shows only one instance where canopy classes melted out at different timings, in January of Water Year 2015.

Hemispherical-photographs

When examining the correlation between sky-view fraction and maximum snow depth from every other zenith angle from nadir to the extent of the hemispherical photographs taken on site (82 degrees) for all 251 measurement points, it was found that the use of a 30-degree zenith angle on the hemispherical photographs provided the sky-view fraction that best explained the most variance in maximum recorded snow depth. The maximum R^2 value between calculated sky-view fraction and maximum recorded snow depth was 0.25 for both maximum accumulation surveys taken in 2013 and 2014, (Figure 12). If the photographs are binned by treatment, the calculated sky-view fractions at a 28˚ and 30˚ zenith angle correlated the best with the maximum snow depths recorded in the control units, with an R^2 value of 0.29 and 0.37 for water years 2013 and 2014, respectively. Within the variable treatments, the best correlation between sky-view fraction and maximum snow depth fell between 36 and 30 degrees zenith and had maximum R^2 values of 0.20 and 0.19 for water years 2013 and 2014. The even treatment had the worst correlation with sky-view fraction and snow depth, with the greatest R^2 being 0.05 and 0.13 for water years 2013 and 2014 and at zenith angles of 26 and 82 (Figure 13). Table 1 summarizes these findings.

Canopy closure for the entire study site was calculated from the hemispherical photographs using the 30˚ zenith angle as this angle provided the greatest correlation to maximum snow depth for both water years surveyed, (Figure 12). It was found that the average canopy closure for the control treatments was approximately 52% and the even and variable units had average canopy closure of 35% and 32% (Figure 14). While the forest-thinning treatments reduced canopy closure by 17-20% overall, it was found that the two thinning treatment's canopy closure percentages were not statistically indistinguishable from one another ($p=0.15$). It was also found that the three canopy classes that were observationally determined during the snow surveys did, in-fact, have statistically different canopy closure values ($p<0.05$). The mean canopy closure values for the open, drip edge, and under class were 24.8, 38.7, and 53.4%.

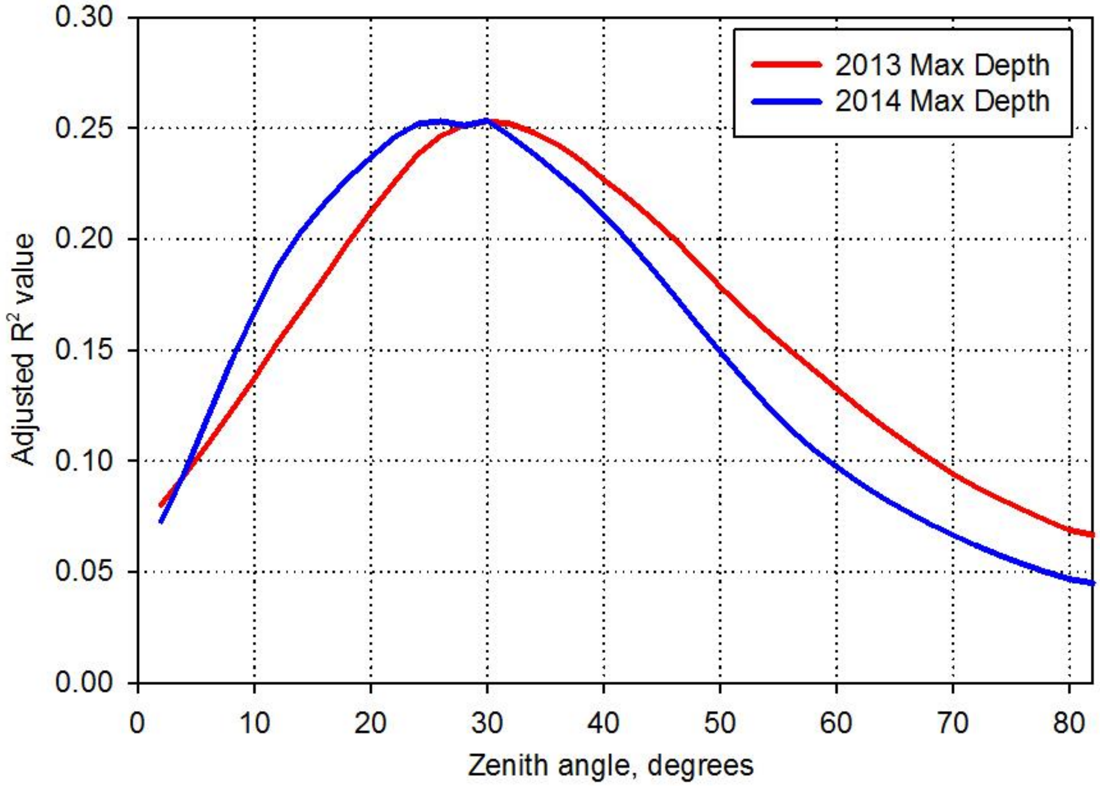

Figure 12. Results from hemispherical-photo analysis. Depicts average zenith angle used to capture sky-view fraction from all 251 measurement points and the corresponding R^2 value when comparing sky-view fraction with maximum accumulated snow depth for both 2013 and 2014.

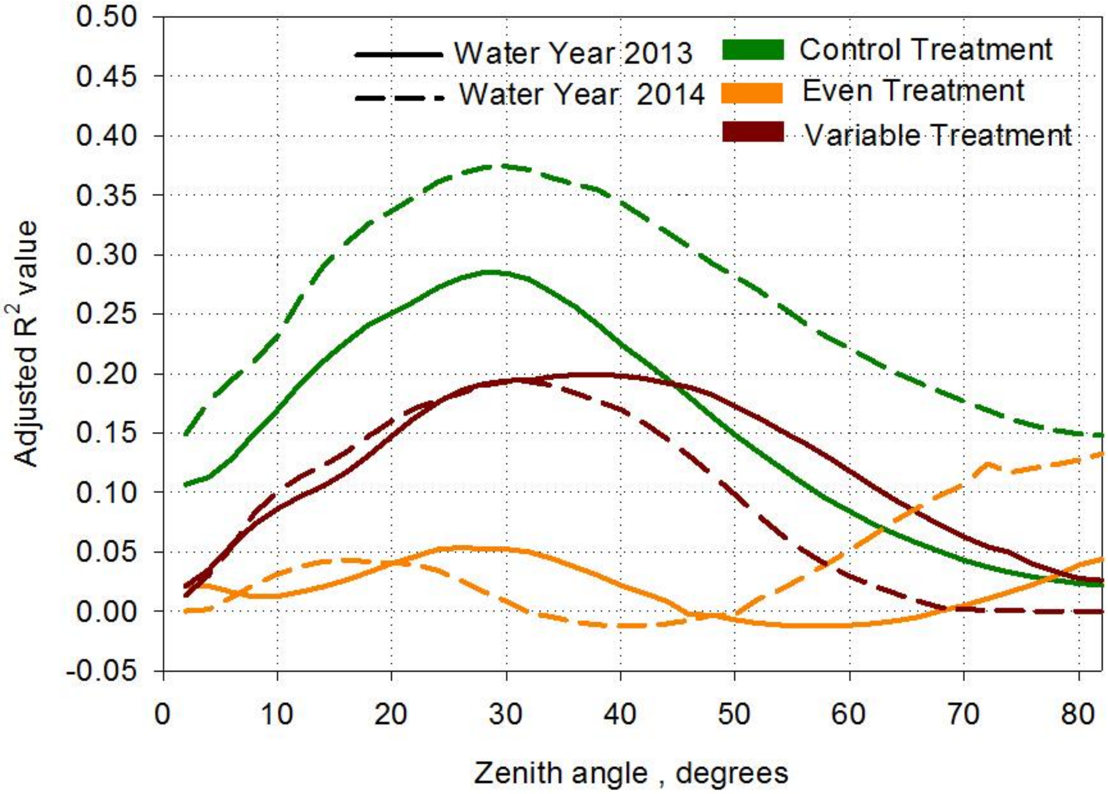

Figure 13. Results from hemispherical-photo analysis. Depicts zenith angle used to capture sky-view fraction from all 251 measurement points and the corresponding R^2 value when comparing sky-view fraction with maximum accumulated snow depth broken up by treatment and water year.

Table 1. Shows optimal zenith angle and corresponding R^2 value, in parenthesis, calculated for the entire study site and for each forest treatment for water years 2013 and 2014.

Water year	All	Control	Even	Variable
2013	30 (0.25)	28 (0.29)	26 (0.05)	36 (0.20)
2014	30 (0.25)	30 (0.37)	82 (0.13)	30 (0.19)

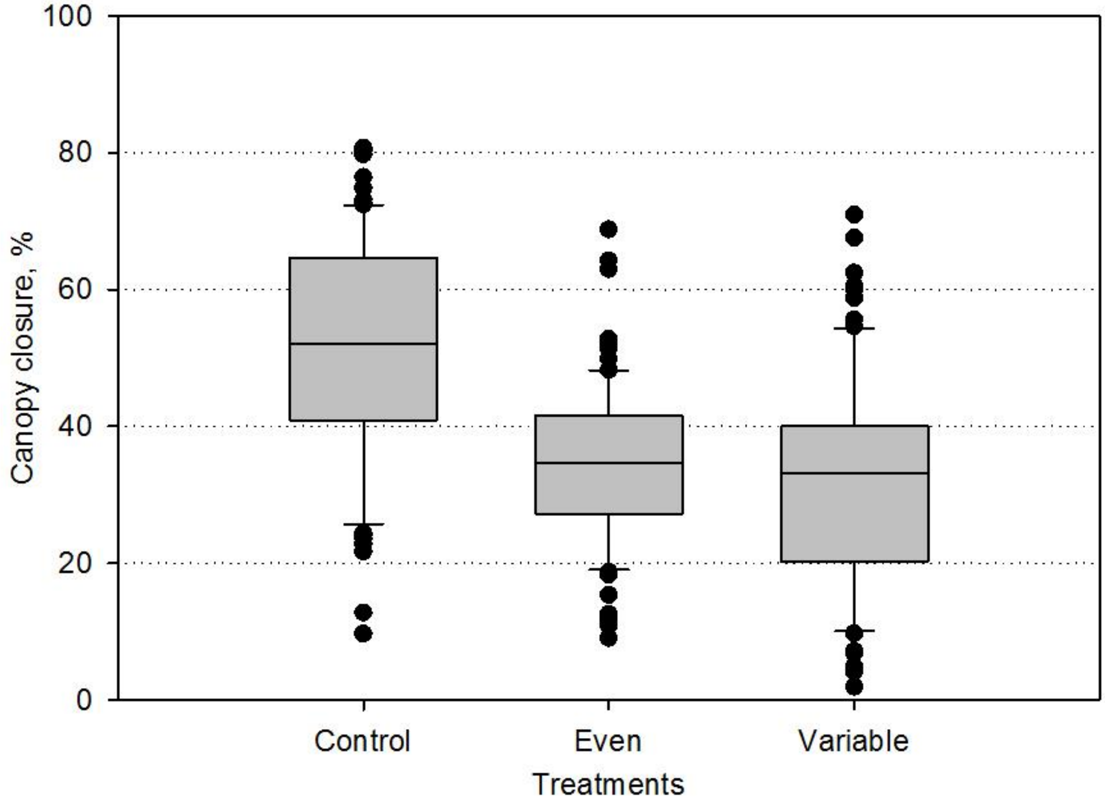

Figure 14. Canopy closure for both forest thinning treatments and control.

LiDAR analysis

The LiDAR dataset provided from NASA JPL allowed us to calculate canopy cover and conversely see how much open/bare ground was available in each of the treatments. Results from this analysis show that the control units on average contain 87% canopy cover (Table 2). The even and variable forest thinning treatments reduced the average overhead canopy coverage by 26 and 30%, resulting in an average of 61 and 57% canopy coverage respectively. It was found that the variable thinning treatment removed an average of 4% more canopy cover than the even treatment ($p=0.03$). Figure 15 showcases the presence and absence of canopy coverage within the study site.

Table 2. Results from LiDAR data depicting area in each unit comprised of canopy cover and bare ground.

Unit	Treatment	Bare ground, m^2	Canopy cover, m^2	Canopy cover, %
3	Control	7515	35108	82.37
6	Control	3945	37314	90.44
7	Control	3112	33373	91.47
12	Control	4708	44477	90.43
14	Control	6761	37641	84.77
16	Control	6472	41024	86.37
19	Control	7070	33718	82.67
20	Control	6187	40232	86.67
1	Even	14665	24682	62.73
4	Even	15108	27414	64.47
9	Even	18610	29170	61.05
11	Even	13526	22692	62.65
13	Even	21670	30554	58.51
17	Even	17989	23597	56.74
23	Even	15908	25268	61.37
24	Even	19823	27986	58.54
2	Variable	20082	25319	55.77
5	Variable	18919	26035	57.91
8	Variable	16263	25591	61.14
10	Variable	14841	21219	58.84
15	Variable	22935	21342	48.20
18	Variable	22287	24000	51.85
21	Variable	18916	24605	56.54
22	Variable	16794	25325	60.13

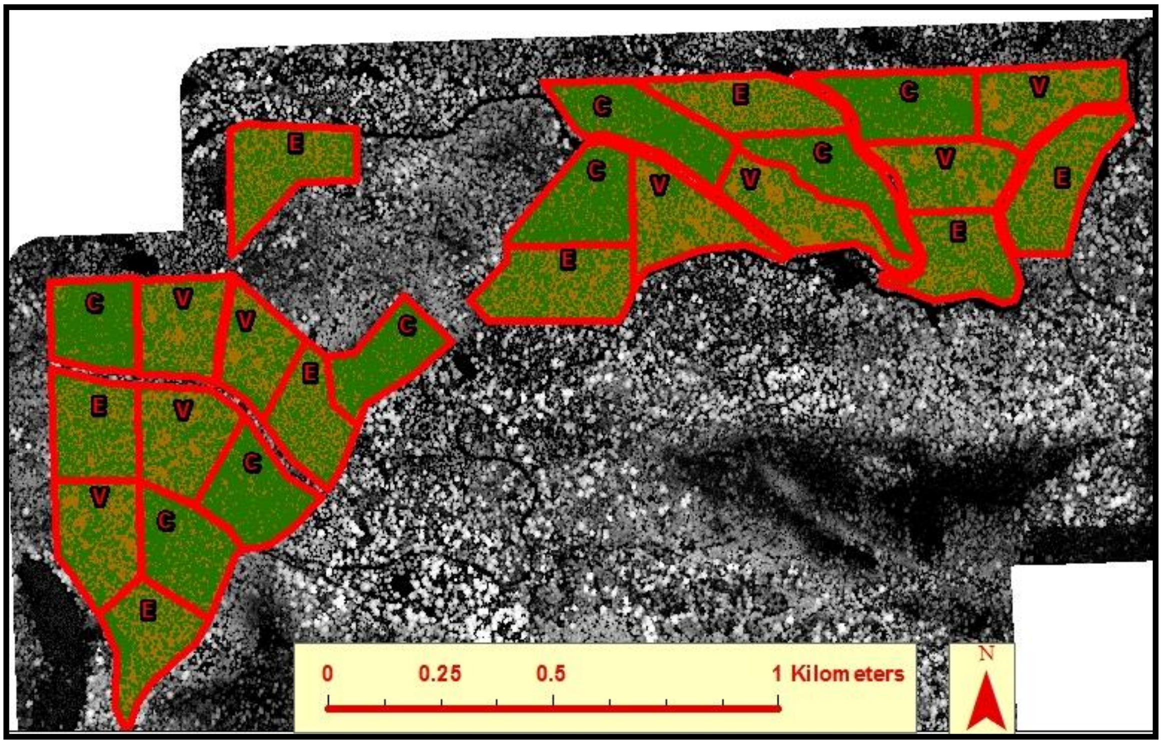

Figure 15. LiDAR derived map of study area indicating areas within each treatment unit with bare ground and canopy cover. Different treatments are indicated by one letter indicators: “C” indicates control treatment, “E” indicates even treatments, “V” indicates variable treatment.

Discussion

While the snow-survey data for both years did show significant differences in snow depth between the control treatment and the two thinning treatments, the spatial pattern of residual trees left within the even and variable thinning treatments had little effect on maximum snow accumulation in either years. The peak-accumulation survey results from 2013, even though still a dry year with low overall snowpack, were likely more indicative of a typical water year than the peak-accumulation results from 2014, mainly because there was a persistent snowpack that started in mid-December and lasted through mid-March that was not present in 2014. The snow-survey results from spring 2014 were for accumulation from a single storm, and provided less insight into seasonal snow patterns for this elevation. In 2013 and 2014 we recorded 20% and 10%, or 7.6 and 3.8 cm, more snow accumulating in the two treated units than in the control, which matches well with results published in Bales et al., (2011). It is good to note, however, that the entirety of the project occurred within one of the worst drought periods in recorded history for the state of California, with both years that snow surveys were conducted having below-normal snowfall and warmer temperatures with the lower-elevation snow courses in the Tuolumne basin reporting 45% of average snow water equivalent for March 2013 and 11% of average for April 2014.

Results from both peak-accumulation surveys show that more snow accumulates in open canopy gaps with less in the drip edge and under the forest canopy. Kirchner, (2013) found between 12-24% shallower snow depth under forest canopies than out in the open. The results from this study match Kirchner's in that we measured 23% more snow in the open in 2013 and 18% more snow in the open in 2014 than under the forest canopy. These results are consistent with findings by Kirchner, (2013) in that the canopy openings that the forest gaps created in the variable treatments contained a statistically significant greater snow depth than the rest of the unit; however when comparing open-canopy snow depth in the variable treatment to the even treatment, there was no statistical difference. Kirchner, (2013) attempted to relate forest canopy cover to snow density, and found that in the accumulation stages of a growing snowpack in the early parts of winter and spring, snow density was only about 2-5% higher under the canopy; and during the ablation period, it was approximately 2-5% higher in the open. Given these small differences, we did not pursue measuring density differences.

It was found that aspect played a minor role in snow distribution at this study site. In 2013 the northeast aspect stood out statistically from the rest. Our results match what Anderson, (1967) showed in that forest thinning will have the greatest effect on snow accumulation on north aspects. It is believed that this is likely due to wind redistribution of the snowpack, moving the snow from the windward side, the southwest, to the leeward side, the northeast, of the hillslope as discussed in Winstral et al., (2002). In 2014, no one aspect stood out from the rest. It is believed that this would be due to the fact that the 2013 peak-accumulation survey measured the product of multiple snow storms accumulating over approximately three months with lots of time for mid-season ablation and wind redistribution; while the 2014 peak accumulation survey only measured the effects of one particular snow storm (Figure 16). Figure 16 shows the hourly and average daily wind speeds as well as survey dates and precipitation measured from the meteorological stations. It is apparent that during the time of the March 29-31 storm, average daily wind speeds did not peak above

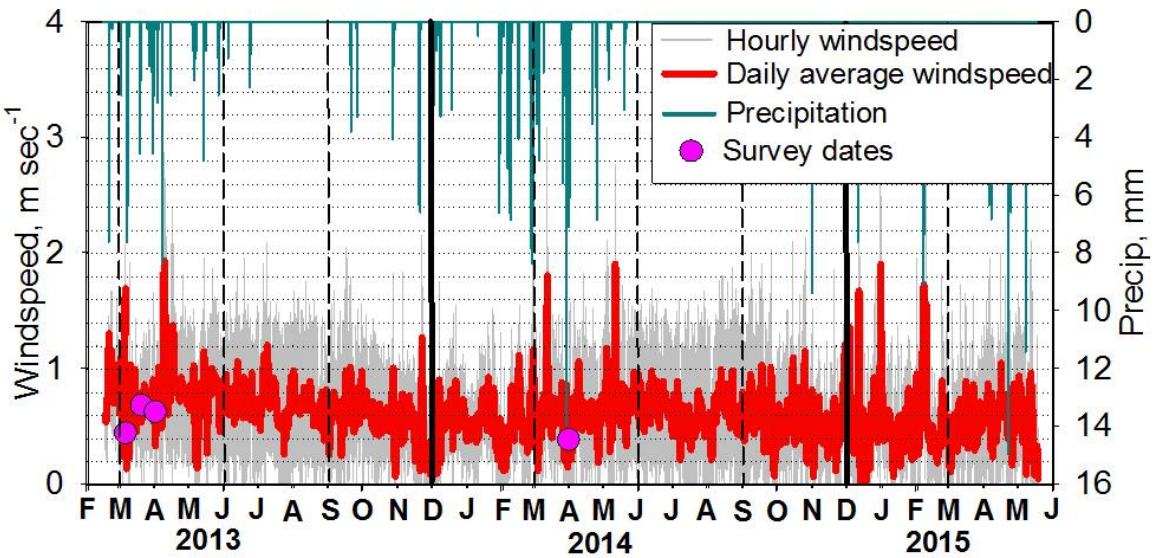

Figure 16. Shows hourly and daily average wind speed along with hourly precipitation. Snow survey dates and the daily average wind speed are plotted together to show that when conducting the surveys, wind speeds were lower than average and wind redistribution of the snowpack more than likely played a minor role in the snow distribution measured.

1 m s^{-1}, while prior to the 2013 peak accumulation survey there were windier days, with daily average wind speeds reaching up to 1.8 m s^{-1}.

The two subsequent snow surveys conducted in the winter of 2013 were instrumental in determining differences in snowpack persistence between treatments. The March 21 survey showed that the variable and control units held snowpack longer than the even treatment. Even though approximately 75% of the measurement points had completely melted out and the measurement points that still contained snowpack were patchy, it showed that the variable units retained snowpack longer in a more-normal, wetter, colder year. It is expected that the variable units keep snowpack on the ground longer than the even units due to the presence of gaps where distance to trees is greater. As Pomeroy et al., (2009) pointed out, tree trunks absorb sunlight and emit longwave radiation that melts the snowpack. The even treatment contains evenly spaced tree trunks that are able to receive solar insolation due to the canopy openness, unlike the control units where it is thought that the majority of the sunlight is absorbed by the canopy rather than the tree trunk. The variable units still receive much of the incoming solar radiation on their tree trunks like the even units, and where the tree spacing is similar to the even treatment we would expect to witness similar snowmelt rates. Where the variable treatment has an advantage is in the forest gaps, where at least a portion of the snowpack lies a greater distance from longwave-radiation-emitting tree trunks.

We found it very interesting that there were no measured differences in snow accumulation or ablation between burned and unburned units. Harpold et al., (2014) found that following a large forest fire in New Mexico, peak snow accumulation increased by up to 45%, but ablation rates also increased due to increased insolation and turbulent energy exchange at the snow surface. While the low-intensity prescribed fire that burned in the site did not have the destructive power of a wildfire, the fires that burned on the study site did clear out fuels both on the ground and aerially, caused some tree mortality changing the needles to brown and potentially opened up more forest gaps. The effects of the prescribed fire could most easily be witnessed in the control treatment as there was a lot of understory tree mortality. There was only 5% mortality in trees > 10 cm diameter at breast height so there was minimal overstory structure change. With no significant change in the overstory, it makes sense why there was no difference in snow accumulation between the burned and unburned units. We believe that the increased variability in the estimated melt rate in the control treatment may be explained in part by the additional litter that fell on top of the snowpack from small understory tree mortality in the burn units thus reducing snow albedo and allowing for greater energy inputs from insolation (Figure 10d).

Data from the distributed light and temperature sensors indicated that in water-year 2013, no statistically significant difference in melt-out date were found between the any of the three forest treatments; however the March 21, 2013 snow survey results show that more measurement points maintained snowpack than is represented in the data from the temperature and light loggers (Figures 7b and 10a). It is believed that these differences in melt-out results can be attributed to the fact that the snow surveys take an average of five subsamples covering an area of approximately 27 m^2, while the light/temperature sensors only measure a single point. By the time that the March 21st survey took place, all of the units had patchy snow cover and large persistent snowdrifts were few and far between and mostly seen within the forest gaps created by the variable treatment. We found it interesting that regardless of the snow in the open melting faster than snow under the canopy, the snow found in the forest gaps the greater accumulation of snow in the forest gaps allowed them to persist longer than snow under the canopy in the variable treatment. We were pleased to find that these results to match what was recorded by Kittredge, (1953) where the longest persistent snowpacks were typically found within forest gaps. Lundquist et al., (2013) also showed that snowpack will persist longer in the open than under the canopy in forests with average winter temperatures greater than -1˚ C.

Results from water year 2014 show that both the variable and even treatments melted out faster than the control units, regardless of the greater snowpack that was recorded in the treated units. This could be explained by the fact that the two treated units are more open, allowing for more solar radiation to make contact with the snowpack; and with the snowpack being less sheltered by the overhead and surrounding forest cover, it allows for greater wind speed and turbulent sensible and latent heat flux (Marks and Winstral, 2001). While the two treated units melted out faster than the control treatment, it is interesting to note that data from the temperature/light sensors indicated that the even treatment had an estimated 8% faster melt rate than the variable and control treatments, which had statistically similar melt rates in 2014 (Figure 10d).

It was unfortunate that the snow-depth sensors were not deployed earlier in order to record the maximum snow depth for the 2013 water year. The distributed snow-depth sensors only recorded data from water years 2014 and 2015, in which only one snow survey took place. We found that the distribution of snow-depth sensors gave a better representation of the snowpack throughout the forest than any one sensor, much like what was demonstrated in Kerkez et al., 2012, and matched up very well with the results of the April 1, 2014 snow survey. Results from the snow sensors showed that essentially, in the time recorded, the snowpack melted out at approximately the same time between all three canopy classes (Figure 11). The longest persistent snowpack recorded by the snow depth sensors was in water year 2015, and was established in early December 2014 and melted out in early January of 2015. The canopy gaps accumulate more snow than do the drip-edge and under-canopy points, and actually keep the snowpack for approximately 3 days longer than the drip edge and 2 days longer than snow being held under the forest canopy. We recorded consistently deeper snow depths after snow storms in the open than under the canopy or drip edge, between 7-10 cm, or 20-40%, which is slightly higher than what Kirchner, (2013) recorded; however Kirchner had considerably more sensors for sample points than this experiment. It is also good to note that the snow depths recorded in 2014 and 2015, were approximately 30% of what would have accumulated in a more average water year where snow depth averages around 1 m or more. Possibly the most valuable piece of information learned from these snow data from water years 2014 and 2015, it is at this elevation, the most-persistent snowpack typically forms in December, and in these low-snow drought years, melts out by January rather than in a typical year melting out in April or May.

Elevational differences within the site had weaker signals with regard to maximum snow depth than was expected. The 7.6 and 1.3 cm more snow recorded in the higher elevation units (units 13-24) during peak accumulation in 2013 and 2014 respectively, was much lower than what Kirchner, (2013) measured in the southern Sierra Nevada. Kirchner measured approximately 15 cm increase to snow depth per 100 m increase in elevation. Results from the 2014 and 2013 maximum accumulation snow surveys show snow accumulation of 2.2-12.6 cm per 100 m elevation since the elevational extremes of the Variable Density Thinning Study are approximately 60 m. This elevational difference means that approximately 9 cm more snow should accumulate in the higher elevation units than in the lower. The snow sensors placed at the elevational extremes of the study site recorded up to a 10 cm difference in snow depth within the same canopy class, but typically showed differences of depth less than 6 cm, meaning that in some of the larger storms, we recorded similar results as published by Kirchner, (2013). This weakened signal may be due to the drought and low snow years, warm winter temperatures, our relatively low-elevation study site, and the fact that the snowstorms were all relatively small in size. This difference in results may also be attributed to the fact that our sample size is so small and Kirchner, (2013) was able to analyze snow-on and snow-off LiDAR data at a landscape level.

Data from the hemispherical photographs proved to have many challenges, however our conclusion of using a 30 degree zenith angle to capture the sky-view factor that represented the greatest influence on peak snow accumulation most closely matched other similar analyses performed in the Sierra, but still varied greatly from similar studies elsewhere. In British Columbia, Teti, (2003) found zenith angles between 60-80˚ to be the most effective at estimating peak snow water equivalent, and Varhola, (2013) found that a sky-view factor using a zenith of 45˚ to be the best indicator of snow ablation rates. However, Kirchner, (2013) found that a sky-view factor using a zenith between 1-40˚ to provide the best relationship to peak snow depth as measured by his snow depth sensors in the Sierra Nevada. Musselman et al., (2012) found that the optimal zenith angle to use and capture sky-view factor shifted in all three years that they were performing their experiment (2008-2010) in the Southern Sierras and found the optimal zeniths to range from 45 to 90˚. However it should be noted that they were using a slightly different metric, directional sky view factor, where they incorporated aspect of canopy closure into the analysis to capture radiative forcing.

Our analysis of the hemispherical photographs show that on average, a 30˚ zenith angle best captures that variability of maximum snow depth (Figure 12), however each of the three forest treatments in fact produced differing optimal zenith angles to predict maximum snow depth (Figure 13). We found that for both years the control treatment showed the strongest relationship between overhead canopy cover and maximum snow depth. The variable treatments had the next greatest correlation between sky-view fraction and maximum snow depth, with the greatest R^2 values found between 30 and 40˚ zeniths. The even treatments had the weakest correlation between snow depth and sky-view fraction than the other treatments. It was very interesting to see the even treatment's sky-view factor the highest correlation to snow depth in 2014 using the full view of the hemispherical photograph (Table 1) and that in 2013, there was an upward R^2 trend approaching 82˚. Reasons for the even treatments correlation between sky-view factor and snow depth having a similar pattern as the other two treatments in 2013 may be attributed to the fact that the snowpack experienced some ablation before the maximum accumulation survey took place and ripening and reshaping the snowpack before the storm that occurred on March 6, 2013 (Figure 5). It is also interesting to note that while the variable and even treatments behave similarly with respect to overall snow depth accumulation, they behave quite differently with regard to maximum snow accumulation correlated with sky-view factor. This higher correlation found in the 30-40 degree range of the variable units suggested that the overhead canopy closure had more of an effect on this treatment than the even treatment. The even treatment's snow accumulation, having the greatest correlation to the full photograph in 2014 and showing an increasing trend in correlation to the full photograph in 2013, may be less effected by the overhead canopy closure and may be more dominated by lateral sheltering of adjacent trees.

The fact that the control units have a greater correlation to sky view-factor than the two treated units may be because of the higher density of trees and a blocking of the wind, thus reducing the influence of lateral snow movement through the treatment and giving more focus on the sky-view fraction directly above the measurement point. The variable treatment's presence of high-density clumps of trees spread within the random pattern of gaps, and the even treatment's lack of these higher-density clumps may be the reason that the variable treatments have a higher correlation of maximum accumulated snow depth to sky-view fraction.

The differences in the measurements of canopy cover measured from the LiDAR dataset and canopy closure measured from the hemispherical photos did not appear to be flawed. As pointed out in Jennings et al., (1999) canopy closure and canopy cover are two completely different metrics used by foresters, with closure typically measuring canopy density and looking at how much light typically can enter through the canopy and canopy cover essentially being a binary measurement indicating the presence of any cover overhead. Both measurements have usefulness and perhaps canopy cover might be a better metric for estimating snow accumulation, as our data indicate that the presence of canopy, regardless of canopy density show a 10-20% difference in snowdepth, and canopy closure, while being able to predict 25% of the variability in snow depth, may be a better metric to measure ablation as shown by Musselman et al., (2012) and Varhola, (2013).

The results of the LiDAR spatial analysis showed that while the two treatments have a relatively similar trees per acre stocking, but different spacing pattern, their relative canopy closure is very similar, with the variable units having only approximately 4% less canopy closure space than the even units. This notion matches with the hemispherical photograph data indicating that the variable units and even units show statistically similar sky-view fractions, or canopy closure.

The fact that the variable and even treatments only varied by 4% in amount of canopy cover and that their calculated sky-view fractions were statistically similar helps explain why we didn’t measure significant differences in maximum snow depth between the treatments. Even though this study showed that the even and variable treatments behave differently in terms of meltout on a higher snow year, we have been able to show that these forest thinning treatments are too similar to produce significant differences in snow accumulation.

Conclusions

We found that the forest thinning treatments performed in the Stanislaus-Tuolumne Experimental Forest, which reduced canopy closure by 16-20% and reduced the trees-per-acre by 80% increased snow accumulation by 10-20%, or 3.8-7.6 cm snow-depth, in the two years recorded. We found no significant difference in maximum snow depth between the two forest thinning treatments. Forest canopies reduced snowpack by 18-23%, or 6.7-10.5 cm snow-depth. We found that in small storms that deposited less than 20 cm of snow, the forest canopy reduced snowpack by up to 40% or 8cm.

We were able to show that on extremely low snow years the densely forested control units retained snowpack for approximately three days longer than the two treated units, and that the even treatment had a higher melt rate than the variable or control units. However, in the year that was closest to average (but still far below average), the variable treatment retained more snow longer than did the even treatment, but retained approximately the same amount of snowcover as the control units. Overall, while the variable treatment did not accumulate more snow than the even treatment, the new forest practice of this variable tree spacing retained snowpack longer than the even treatment on a more-average snow year and exhibited reduced melt rates from the current forest practice of even spacing on a very-low snow year, and previous research shows that the forest gaps will maintain snowpack longer than under the canopy. The variable treatment shows potential to slow snowmelt and retain snowpack in the mountains especially if these treatments were conducted on a landscape level. More research is required on this subject to determine if these patterns do indeed hold true on an average to above-average snow year.

References

Adams, M. B., Loughry, L., Plaugher, L. (2004). Experimental Forests and Ranges of the USDA Forest Service. General Technical Report NE-321. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. p. 178 GTR- NE-321.

Agee, J. K., Skinner, C. N. (2005). Basic Principles of forest fuel reduction treatments. *Forest Ecology and Management, 211*, 83-96.

Anderson, H. W. (1967). Snow accumulation as related to meteorological, topographic, and forest variables in central Sierra Nevada, California. *International Association of Scientific Hydrology*, Pp 215-224.

Anderson, H. W., Hoover, M. D., Reinhart, K. G., (1976). Forests and Water: Effects of Forest Management on Floods, Sedimentation and Water Supply. USDA Forest Service, Pacific Southwest Forest and Range Experimental Station, Berkeley, CA, USDA Forest Service General Technical Report PSW 18/1976, 115pp.

Bales, Roger C., Noah P. Molotch, Thomas H. Painter, Michael D. Dettinger, Robert Rice, Jeff Dozier. (2006). Mountain Hydrology of the western United States. *Water Resources Research*, *42*, W08432, doi:10.1029/2005WR004387.

Bales, R. C., Battles, J. J., Chen, Y., Conklin, M. H., Holst, E., O'Hara, K. L., Saksa, P., Stewart, W. (2011). Forests and water in the Sierra Nevada: Sierra Nevada watershed ecosystem enhancement project. *Sierra Nevada Research Institute report*, (11.1).

Bouldin, J. (1999). Twentieth-century changes in forests of the Sierra Nevada, California. Ph.D. dissertation, University of California, Davis. pp 222.

Diffenbaugh, N. S., Swain, D. L., & Touma, D. (2015). Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences*, *112*(13), 3931-3936.

Dore, S., Montes-Helu, M., Hart, S. C., Hungate, B. A., Koch, G. W., Moon, J. B., Finkral, A. J., Kolb, T. E. (2012). Recovery of ponderosa pine ecosystem carbon and water fluxes from thinning and stand-replacing fire. *Global Change Biology*, *18*(10), 3171-3185.

Elder, K., Dozier, J., & Michaelsen, J. (1991). Snow accumulation and distribution in an alpine watershed. *Water Resources Research*, *27*(7), 1541-1552.

Erxleben, J., Elder, K., & Davis, R. (2002). Comparison of spatial interpolation methods for estimating snow distribution in the Colorado Rocky Mountains. *Hydrological Processes*, *16*(18), 3627-3649.

Fites-Kaufman, Jo Ann, Phil Rundel, Nathan Stephenson, Dave Weixelman. (2007). Montane and subalpine vegetation of the Sierra Nevada and Cascade ranges. In: Barbour, M., T. Keeler-Wolf, A. A. Schroenherr (Eds.), *Terrestrial Vegetation of California*. University of California Press, Berkeley, pp 456-501.

Frazer, G.W., C. D. Canham, K. P. Letterman. (1999). Gap Light Analyzer (GLA). Version 2.0: Imaging Software to Extract Canopy Structure and Gap Light Transmission Indices from True-Colour Fisheye Photographs. User's Manual and Program Documentation. Simon Frazer University, Burnaby B.C. and the Institute of Ecosystem Studies, Millbrook, New York.

Golding, D. L., & Swanson, R. H. (1986). Snow distribution patterns in clearings and adjacent forest. *Water Resources Research*, *22*(13), 1931-1940.

Gonzales, P., Battles, J. J., Collins, B. M., Robards, T., Saah, D. S. (2015). Aboveground live carbon stock changes of California wildland ecosystems, 2001-2010. *Forest Ecology and Management, 348,* 68-77.

Hardy, J. P., Davis, R. E., Jordan, R., Li, X., Woodcock, C., Ni, W., McKenzie, J. C. (1997). Snow ablation modeling at the stand scale in a boreal jack pine forest. *Journal of Geophysical Research*. *102,* 397-405.

Hardy, J. P., Melloh, R., Robinson, P., & Jordan, R. (2000). Incorporating effects of forest litter in a snow process model. *Hydrological Processes*, *14*(18), 3227-3237.

Harpold, A. A., Biederman, J. A., Condon, K., Merino, M., Korgaonkar, Y., Nan, T., Sloat, L. L., Ross, M., Brooks, P. D. (2014). Changes in snow accumulation and ablation following the Las Conchas Forest Fire, New Mexico, USA. *Ecohydrology, 7*(2), 440-452.

Hubbart, J. A., Link, T. E., Gravelle, J. A. (2015). Forest canopy reduction and snowpack dynamics in a northern Idaho watershed of the continental-maritime region, United States. *Forest Science, 3,* 1-13.

Jennings, S. B., Brown, N. D., Sheil, D. (1999). Assessing forest canopies and understory illumination: canopy closure, canopy cover, and other measures. *Forestry, 72*(1).

Kattelmann, R. C., Berg, N. H., & Rector, J. (1983). The Potential for Increasing Streamflow from Sierra Nevada Watershed. *JAWRA Journal of the American Water Resources Association*, *19*(3), 395-402.

Kerkez, B., Glaser, S. D., Bales, R. C., & Meadows, M. W. (2012). Design and performance of a wireless sensor network for catchment-scale snow and soil moisture measurements. *Water Resources Research*, *48*(9).

Kirchner, Peter B. (2013). SNOW DISTRIBUTION OVER AN ELEVATION GRADIENT AND FOREST SNOW HYDROLOGY OF THE SOUTHERN SIERRA NEVADA, CALIFORNIA. UC Merced: Environmental Systems. Retrieved from: https://escholarship.org/uc/item/9zn1c1mk

Kittredge, J. (1953). Influences of forests on snow in the ponderosa, sugar pine, fir zone of the Central Sierra Nevada. *Hilgardia*, *22*(2), 1-96.

Knapp, E., M. North, M. Benech, B. Estes. (2012). The variable density thinning study at Stanislaus-Tuolumne Experimental Forest. In "Managing Sierra Nevada forests. USDA Forest Service, Pacific Southwest Research Station General Technical Report PSW-GTR-237." (Ed M. North) pp. 127-139. (Albany, CA).

Knapp, E., C. N. Skinner, M. P. North, B. L. Estes. (2013). Long-term overstory and understory change following logging and fire exclusion in a Sierra Nevada mixed-conifer forest. *Forest Ecology and Management*, *310,* 903-914.

Link, T., Marks, D. (1999). Distributed simulation of snow cover mass- and energy-balance in the boreal forest. *Hydrological Processes*, *13*, 2439-2452.

López-Moreno, J. I., & Latron, J. (2008). Spatial heterogeneity in snow water equivalent induced by forest canopy in a mixed beech–fir stand in the Pyrenees. *Annals of Glaciology*, *49*(1), 83-90.

Lundquist, J. D., Dickerson-Lange, S. E., Lutz, J. A., Cristea, N. C. (2013). Lower forest density enhances snow retention in regions with warmer winters: A global framework developed from plot-scale observations and modeling. *Water Resources Research*, *49*, 6356-6370, doi: 10.1002/wrcr.20504.

Lydersen, J. M., North, M. P., Knapp, E. E., Collins, B. M. (2013). Quantifying spatial patterns of tree groups and gaps in mixed-conifer forests: reference conditions and long-term changes following fire suppression and logging. *Forest Ecology and Management*, *304*, 370-382.

Lydersen, J. M., North, M. P., Collins, B. M. (2014) Severity of an uncharacteristically large wildfire, the Rim Fire, in forests with relatively restored frequent fire regimes. *Forest Ecology and Management*, *328*, 326-334.

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*, 213-227.

Mote, P. W., Hamlet, A. F., Clark, M. P., & Lettenmaier, D. P. (2005). Declining mountain snowpack in western North America. *Bulletin of the American meteorological Society*, *86*(1), 39-49.

Mote, P. W. (2006). Climate-driven variability and trends in mountain snowpack in western North America. *American Meteorological Society, 19*, 6209-6220.

Musselman, K.N., N. P. Molotch, P. D. Brooks. (2008) Effects of vegetation on snow accumulation and ablation in a mid-latitude sub-alpine forest. *Hydrologic Processes*, *22*, 2767-2776.

Musselman, K. N., Molotch, N. P., Margulis, S. A., Kirchner, P. B., & Bales, R. C. (2012). Influence of canopy structure and direct beam solar irradiance on snowmelt rates in a mixed conifer forest. *Agricultural and Forest Meteorology*, *161*, 46-56.

North, M., Stine, P., O'Hara, K., Zielinski, W., Stephens, S. (2009). An Ecosystem Strategy for Sierran Mixed-Conifer Forests. Pacific Southwest Research Station General Technical Report PSW-GTR 220.

Pomeroy, J. W., R. A. Schmidt. (1993). The use of fractal geometry in modelling intercepted snow accumulation and sublimation. *Eastern Snow Conference*, *50*, 1-10.

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.

Pomeroy, J. W., Toth, B., Granger, R. J., Hedstrom, N. R., & Essery, R. L. H. (2003). Variation in surface energetics during snowmelt in a subarctic mountain catchment. *Journal of Hydrometeorology*, *4*(4), 702-719.

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. *Hydrological processes*, *23*(17), 2513.

Rice, R., & Bales, R. C. (2010). Embedded-sensor network design for snow cover measurements around snow pillow and snow course sites in the Sierra Nevada of California. *Water resources research*, *46*(3).

Rice, R., Bales, R. C., Painter, T. H., Dozier, J. (2011). Snow water equivalent along elevation gradients in the Merced and Tuolumne River basins of the Sierra Nevada. *Water Resources Research*., *47*, W08515, doi:10.1029/2010WR009278.

Stephens, S. L., Moghaddas, J. J., Edminster, C., Fiedler, C. E., Haase, S., Harrington, M., Keely, J. E., Knapp, E. E., McIver, J. D., Metlen, K., Skinner, C. N., Yougnblood, A. (2009). Fire treatment on vegetation structure, fuels, and potential fire severity in the western U.S. forests. *Ecological Applications*, *19*(2), 305-320.

Storck, P., Lettanmaier, D. P., Bolton, S. (2002). Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. *Water Resources Research. 38*(11), 1223, doi:10.1029/2002WR001281, 2002.

Teti, P. (2003). Relations between peak snow accumulation and canopy density. *The Forestry Chronicle, 79*(2), 307-312.

Troendle, C. A., & King, R. M. (1985). The effect of timber harvest on the Fool Creek watershed, 30 years later. *Water Resources Research*, 21(12), 1915-1922.

Troendle, C. A., Wilcox, M. S., Bevenger, G. S., & Porth, L. S. (2001). The Coon Creek water yield augmentation project: Implementation of timber harvesting technology to increase streamflow. *Forest Ecology and Management*, 143, 179-187.

Varhola, A., Coops, N. C., Alila, Y., & Weiler, M. (2014). Exploration of remotely sensed forest structure and ultrasonic range sensor metrics to improve empirical snow models. *Hydrological Processes*, 28(15), 4433-4448.

Veatch, W. C. (2008). Quantifying the Effects of Forest Canopy Cover on Net Snow Accumulation at a Continental, Mid-latitude Site, Valles Caldera National Preserve, New Mexico, USA. M.S. Thesis, University of Arizona, Tuscon, AZ.

Veatch, W., P. D. Brooks, J. R. Gustafson, N. P. Molotch. (2009). Quantifying the effects of forest canopy cover on net snow accumulation at a continental, mid-latitude site. *Ecohydrology*, 2, 115-128.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., Swetnam, T. W. (2006). Warming and earlier spring increase western U.S. forest fire activity. *Science*, 313(5789), (940-943).

Winstral, A., Elder, K., & Davis, R. E. (2002). Spatial snow modeling of wind-redistributed snow using terrain-based parameters. *Journal of Hydrometeorology*, 3(5), 524-538.

Appendix A

All data may be digitally download here:

https://eng.ucmerced.edu/snsjho/files/MHWG/Field/STEF?sort_on=id&sort_dir=asc

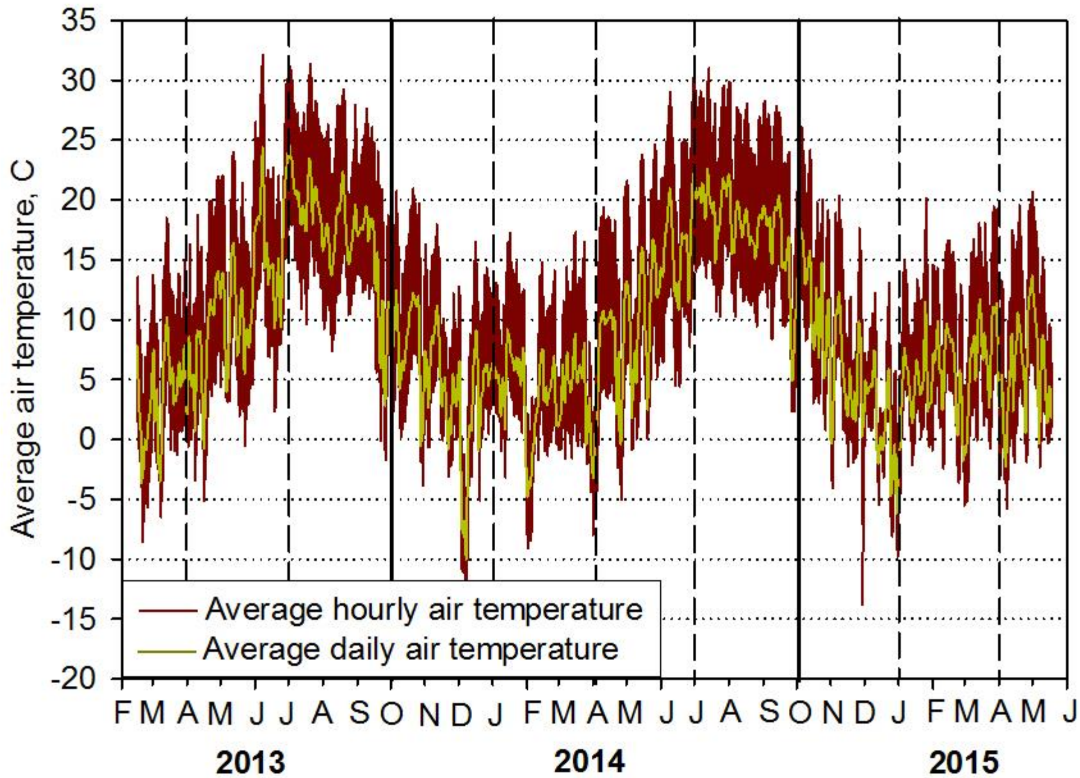

Figure A-1. Daily and hourly average air temperature recorded from met tower located in Unit 21.

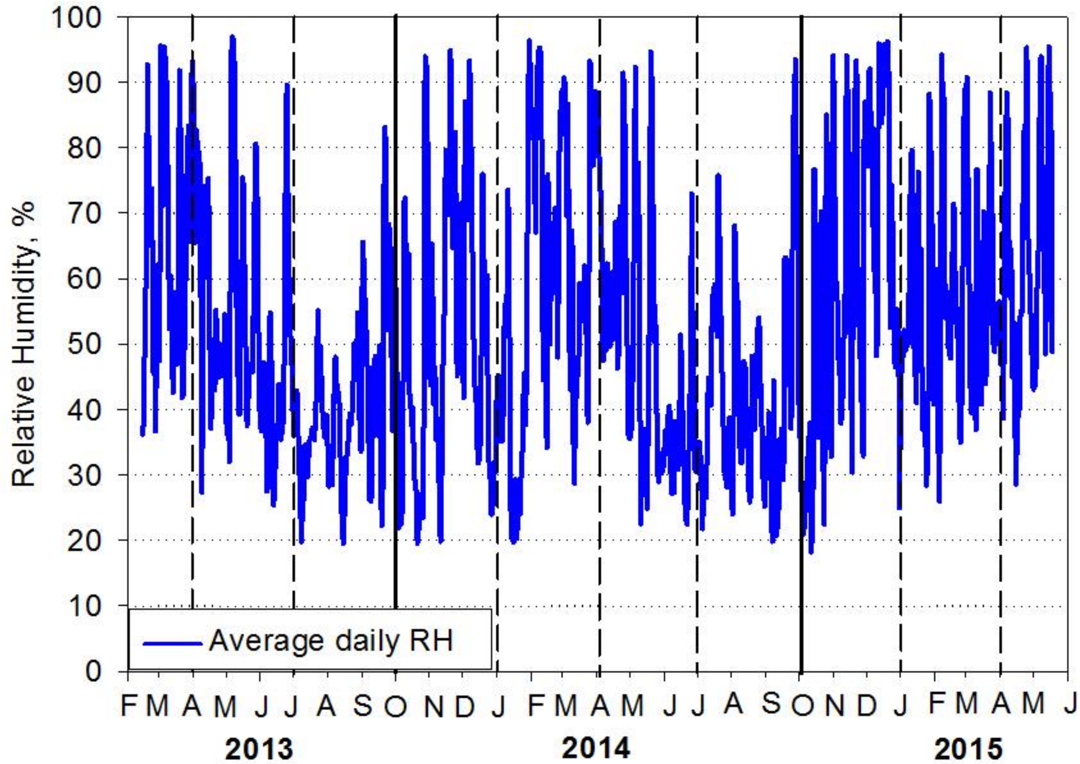

Figure A-2. Daily average relative humidity measured from meteorological tower located in unit 21.

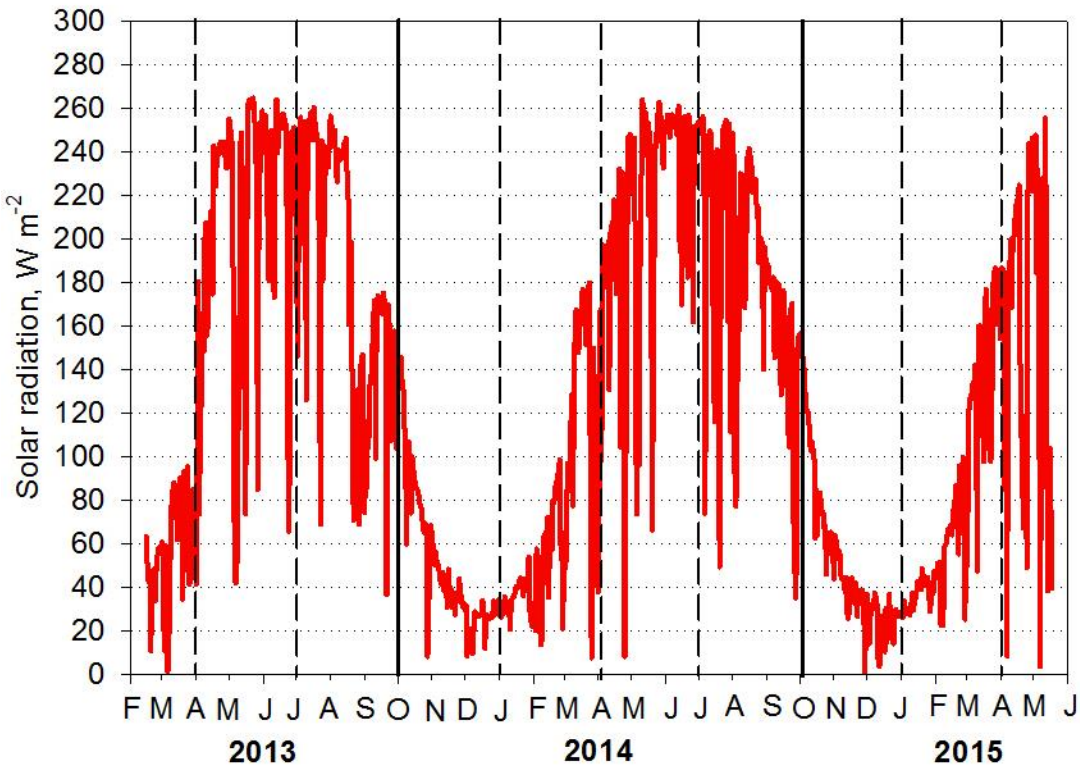

Figure A-3. Daily average incoming solar radiation measured from meteorological station located in unit 21.

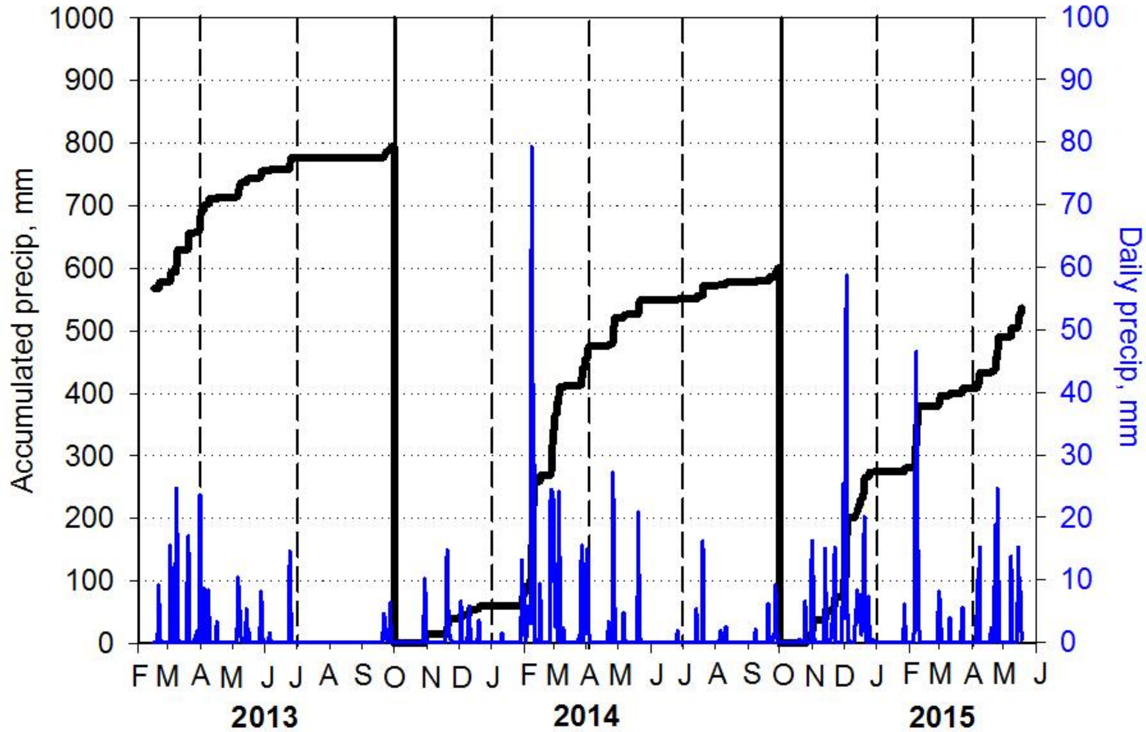

Figure A-4. Daily and accumulated precipitation measured from meteorological station in unit 21. Accumulated precipitation data prior to tower deployment (February 2013) was gathered from Pinecrest Lake weather station (PCR).