Determining Optimal Canopy Cover and Terrain Features for Snow Accumulation and Retention in the Owens River Headwaters Wilderness, CA

Hayden J. Street

ABSTRACT

Snowmelt from the Sierra Nevada mountain range comprises at least 30% of California's water supply. Climate change is the main threat to the state's water resources as rising temperatures and drought will reduce the springtime snowpack volume by more than 25% by 2050 and cause melting to occur faster and earlier in the year. Silviculture, or the practice of modifying forest structure, is one method which can help mitigate the effects of climate change on water resources. Using remotely sensed data, I aimed to inform forest management by conducting one-way ANOVA tests to determine what percent canopy cover resulted in the greatest peak snow water equivalent (SWE) and longest melt duration. I performed Pearson correlation tests and linear regression analysis to determine the effect of elevation, aspect, and slope on snowpack processes. Low canopy cover (0-25%), had the greatest peak SWE on average, but the shortest melt duration. High canopy cover (50-75%), had slightly less snow accumulation, but significantly longer melt times. The terrain analysis showed a statistically significant positive relationship for elevation and aspect between peak SWE and melt duration, but a comparatively weak effect from slope. The results indicate that the optimal forest structure, with regard to maximizing water resources, is high density forest (50-75% canopy coverage) to prolong melting with pockets of open areas to accumulate snow without interference from canopy interception. Silvicultural practices can be optimized by concentrating on north facing slopes at elevations between 2300 and 2500 meters.

KEYWORDS

Climate change, silviculture, snow hydrology, Eastern Sierra Nevada, water resource management

INTRODUCTION

The Sierra Nevada snowpack is a vital source of fresh water for California's population and agriculture industry, but climate change presents serious challenges for the water supply. Climate change will exacerbate drought and dangerous fire conditions, shrink the snowpack, and cause demand for water to rise as temperatures increase over the next century (Reich et al. 2018). This poses a serious threat to California's water needs as 60% of the population and 75% of water for the state's 50-billion-dollar agriculture sector is supplied by runoff from the Sierra Nevada (Podolak et al. 2015). It is estimated that one third to one half of California's total water supply is from the Sierra Nevada snowpack. Under business-as-usual climate models, 64% of the springtime snowpack will be gone by the end of the century, and 25% will disappear by 2050 (Reich et al. 2018). Increasing temperatures will also lead to earlier and more rapid snowmelt, rather than a gradual melt that fulfills demand for water over spring, summer, and fall (Kattelman 1983). Moreover, rising temperatures will cause more precipitation to fall as rain instead of snow, limiting the amount of water held by snowpack, and therefore the amount of runoff available for future use (Kapnick and Hall 2010). As a result, there is a need for additional research examining potential methods of bolstering water resources by increasing snow accumulation and extending melt duration.

Silviculture, the practice of modifying forest structure and composition, is one possible way to mitigate the effect of climate change on water resources by manipulating the water and energy budget within forest ecosystems. Forests influence the water budget by intercepting snow in the canopy where it is more exposed to wind and solar radiation, increasing the likelihood it sublimates before collecting on the ground. Up to 40% of the total snowfall in a forested region can be sublimated before it accumulates in the snowpack (Hedstrom and Pomeroy 1998). Vegetation cover also strongly influences the energy budget by determining how much incident solar radiation is reflected, transmitted, or absorbed (Pomeroy et al. 1998). Shortwave radiation from the sun is absorbed by the canopy and trees and is re-radiated as longwave radiation to the surrounding environment, which can increase melting. Contrarily, trees and canopy cover provide shade and wind protection to sub-canopy snow, prolonging melt duration by blocking solar radiation and preventing the snow from being blown away (Bales et al. 2011). Consequently, there is a delicate balance between the impacts of forests on the energy budget that makes it difficult to predict whether the presence of vegetation will increase or decrease melt duration (Ellis 2010). In temperate montane environments like the Sierra Nevada, sub-canopy snow typically melts quicker compared to open areas because of warmer winter temperatures favoring longwave radiation as the primary melt driver (Lopez-Moreno and Latron 2008). Therefore, strategically modifying vegetation cover in a watershed has potential to mitigate the effects of climate by increasing snowpack volume and extending melt duration.

However, the processes affecting snow accumulation and retention are further complicated by topography, the three major variables being elevation, aspect, and slope. Topography in the Sierra Nevada is highly variable, causing drastic differences in weather conditions even over small horizontal distances of a few kilometers (Ma et al. 2010). Elevation influences the water and energy budget due to orographic lifting of air parcels; as air rises up the face of a mountain, it cools adiabatically, leading the air to condense and precipitate, causing more snowfall and reduced melt rates at higher altitudes (Lundquist et al. 2010). Aspect, or the direction that a mountain is positioned (e.g. north, east, south, west), determines the amount of incident solar radiation in an area. Because Earth is tilted on its axis as it orbits around the sun, the solar geometry causes an unequal distribution of radiation with regard to aspect (Musselman et al. 2012). Lastly, slope plays an important role in the distribution of the snowpack, where steeper slopes usually accumulate less snow because of greater gravitational forces (Sommer et al. 2015). Because environmental conditions can vary significantly over small spatial extents from the heterogeneous terrain, any potential forest management plan to maximize water resources should be catered to the specific meteorological and topographical features of the landscape (Lundquist 2013). For this reason, I aimed to inform silvicultural practices for an important watershed in the Eastern Sierra Nevada by investigating the effect of canopy cover and topography on snowpack accumulation and melting. To accomplish this, I framed my research around three specific sub-questions: 1. What is the optimal amount of canopy cover to maximize snow water equivalent (SWE), or the amount of liquid water remaining if the snowpack were to melt completely? 2. What is the optimal amount of canopy cover to maximize melt duration? 3. What elevation, aspect, and slope resulted in the greatest peak SWE and melt duration?

METHODS

Study site

The study site I chose is the Owens River Headwaters Wilderness in the Eastern Sierra Nevada, California (Figure 1). The Owens River Headwaters Wilderness is 14,721 acres of predominantly red fir forest with expansive meadows located in the Inyo National Forest. Although the eastern side of the Sierra Nevada is usually dry due to rain shadow effects, the crest of the mountain range is lower in this region, allowing moisture to be carried over and precipitated. The runoff from the unusually high rainfall and snowmelt drains into Mono Lake Basin and forms the Owens River, which provides 430 million gallons of water per day to Los Angeles, or one third of the city's water supply.

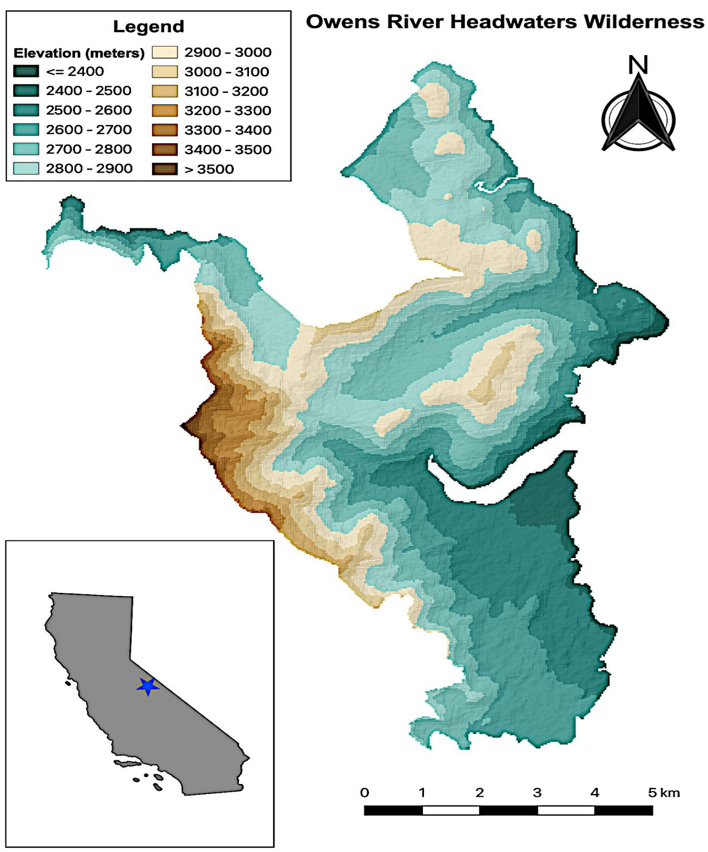

Figure 1. Topographic map of study site. Owen's River Headwaters Wilderness ranges from 2300 to 3600 meters above sea level. Elevation data was divided into discrete 100-meter contour intervals and displayed using a color gradient, where each contour was assigned a unique color.

Data collection

I downloaded 2011 canopy cover raster data from the USDA Forest Service website, which estimates percent canopy cover at a 30-meter resolution using LANDSAT satellite imagery (https://data.fs.usda.gov/geodata/rastergateway/treecanopycover/). I acquired a 1 Arc-second digital elevation model (DEM) from the US Geological Survey using the USGS Earth Explorer website (https://earthexplorer.usgs.gov). Lastly, I obtained snowpack reanalysis data published by the Margulis lab at UCLA (Margulis et al. 2015; Margulis et al. 2016). This dataset models snow water equivalent (SWE) over time and space at a 90-meter resolution using remotely-sensed snow cover data from LANDSAT satellites and meteorological inputs. Each raster pixel in the dataset has 365 bands of data, where each band represents daily SWE values for the entire 2011 water year, starting on October 1, 2010 and ending on September 30, 2011.

Data processing

I uploaded the dataset to QGIS version 3.16- Hannover for processing. First, I used the cubic convolution resampling method to upscale the resolution of the canopy cover dataset and digital elevation model to match the SWE dataset at 90 meters. Next, I conducted terrain analysis with the DEM to calculate aspect and slope. Aspect data are expressed in degrees between 0 and 360, where 0 degrees is north, 90 degrees is east, 180 degrees is south, and 270 degrees is west. I converted aspect into northness by taking the cosine of the raw aspect value. This changes the degree aspect data into a value from -1 to 1, where -1 is south and 1 is north. Slope data are expressed in degrees between 0 and 90, where 0 degrees represents a flat surface and 90 degrees represents a vertical surface. Then, I sampled each raster cell to extract SWE, elevation, aspect, northness, and percent canopy cover values. This step resulted in a complete dataset with 6290 90-meter pixels. Finally, I binned the data into 3 groups based on low, medium, or high percent canopy cover: 0-25%, 25-50%, and 50-75%, respectively.

Determining optimal canopy cover for SWE

I calculated peak SWE for each pixel by extracting the maximum SWE value during the 2011 water year. I used a Pearson correlation analysis to determine if there was a statistically significant relationship between percent canopy cover and peak SWE. To evaluate which canopy cover group resulted in the most SWE, I conducted a one-way ANOVA with a Welch correction to test for a statistically significant difference in group SWE means. Lastly, I used a Games Howell post hoc test to find which pairwise comparisons of canopy cover groups had statistically significant differences in peak SWE.

Determining optimal canopy cover for melt duration

I found the melt duration for each raster cell by measuring the number of days it takes for the April 1 SWE value to be reduced by 85%. Occasionally, an area may take several weeks for a small amount of remaining snow to melt or does not melt at all due to cold temperatures year-round at high elevations. Because the focus of this thesis is maximizing usable runoff for human use or ecosystem processes during melt season, a cutoff of 15% remaining SWE captures the most important snowmelt contribution without as much error from anomalies in melt rates. I used a Pearson correlation analysis to determine if there is a statistically significant relationship between percent canopy cover and melt duration. To determine which canopy cover group experienced the longest melt time, I performed a one-way ANOVA with a Welch correction to test for a statistically significant difference in group melt duration means. Lastly, I used a Games Howell post hoc test to ascertain which pairwise comparisons of canopy cover groups had statistically significant differences in melt duration.

Determining effect of topography

I examined the influence of three terrain variables on the snowpack: elevation, northness, and slope. For each variable, I conducted a Pearson correlation analyses to test for a statistically significant relationship with peak SWE and melt duration. To gauge the effect size of each variable, I calculated the standardized coefficient (β) using linear regression with elevation, northness, and slope as predictor variables and melt duration and peak SWE as dependent variables. Standardized beta coefficients range from -1 to 1 and are a measure of the response of the dependent variable to changes in predictor variables, normalized by standard deviation. For example, a beta value of 0.5 means that for every 1 standard deviation increase in a predictor variable, the response variable is increased by 0.5 standard deviations.

RESULTS

Effect of canopy cover on snow water equivalent (SWE)

Percent canopy cover and peak snow water equivalent (SWE) were weakly correlated (r = -.081). Generally, the results indicate a negative relationship between canopy cover and peak SWE when coverage is under 40%; above 40%, there was a positive relationship whereby higher canopy cover values corresponded with greater peak SWE (Figure 2). Average peak SWE for the Owens River Headwaters Wilderness was 943.3 ± 219.0 mm (Table A1). Maximum SWE occurred in the 0 -25% canopy cover group (980.2 ± 258.9 mm), whereas SWE was lowest in the 25-50% group (863.0 ± 188.1 mm). The 50-75% group had peak SWE values of 969.6 ± 142.1 mm (Figure 3). A Pearson correlation test found that the relationship between peak SWE and canopy cover was significant ($p < .001$).

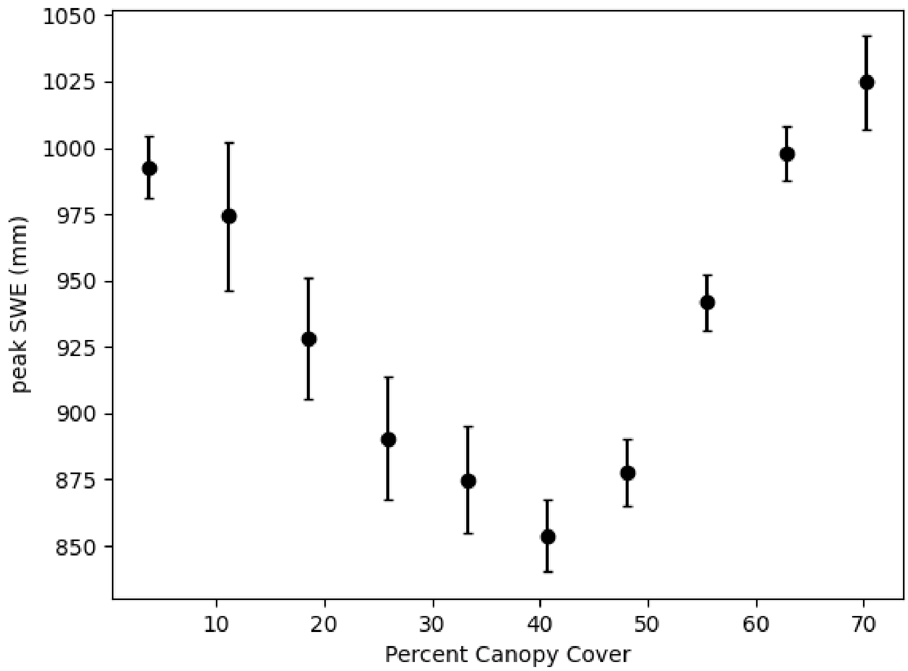

Figure 2. Binned scatter plot comparing peak SWE and percent canopy cover. (n = 6290). Percent canopy cover data was divided into 10 equal intervals. Average peak SWE was calculated for each bin and plotted as points with corresponding 95% confidence intervals, represented by the error bars. The range of values within the error bars are 95% likely to contain the true average peak SWE value.

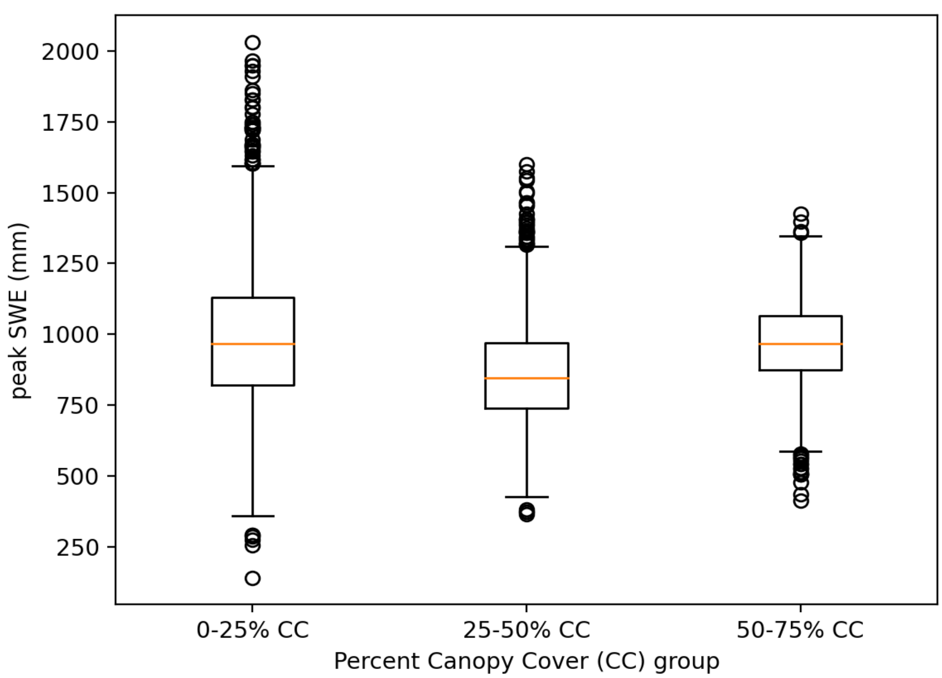

Figure 3. Comparison of peak SWE between low (0-25%), medium (25-50%), and high (50-75%) canopy cover groups. The box-and-whisker plot summarizes group differences in peak SWE. The orange line in each box is the median peak SWE value, while the top and bottom edges of the box mark the upper and lower quartiles, respectively. The top whisker represents the range of values in the upper 25% of data, while the bottom whisker represents the range of values in the lower 25% of data. Data outside the whiskers are outliers.

There was a statistically significant ($p < .001$) difference in SWE between canopy cover groups as determined by a one-way ANOVA test (Table A2). A Games Howell post hoc test revealed that peak SWE was statistically significantly lower for 25-50% canopy cover ($p < .001$) compared to the 0-25% group and 50-75% group. However, the 0-25% group did not statistically significantly differ from the 50-75% group ($p = .179$). As a result, I rejected the null hypothesis that there were no statistically significant differences between canopy cover groups; however, only comparisons including the 25-50% group were significant.

Effect of canopy cover on melt duration

During the 2011 water year, SWE for each canopy cover category peaked on March 26, and rapidly declined starting in early April (Figure 4).

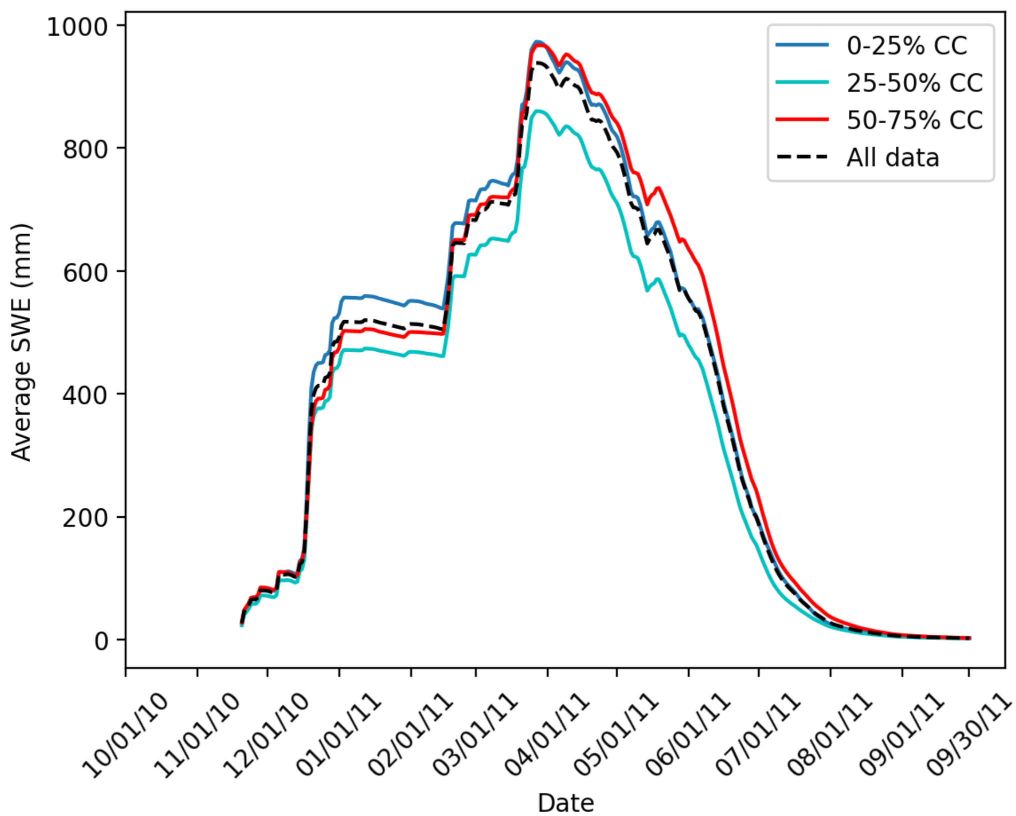

Figure 4. Time series for SWE during the 2011 water year. The water year started on October 1, 2010 and ended on September 30, 2011. All zero SWE values before the first snow event were removed. Each line represents averaged daily SWE values for canopy cover groups. The blue line represents low canopy cover under 25%; the cyan line represents medium canopy cover within 25-50%; the red line represents high canopy cover above 50%, and the dotted black line is the raw data before being divided into groups.

From the Pearson correlation analysis, I found the relationship between melt duration and percent canopy cover to be statistically significant ($p < .001$). Melt duration and canopy cover were positively correlated ($r = .263$); canopy covered areas retained snow longer than in clearings (Figure 5). Average melt duration for the Owens River Headwaters Wilderness was 90.3 ± 14.2 days. The 50-75% canopy cover group took the longest time to melt (96.6 ± 10.3 days), whereas average melt duration was lowest in the 0-25% group (87.2 ± 17.1 days). The 25-50% group had average melt duration times greater than the 0-25% group, but less than the 50-75% group with a value of 89.5 ± 10.3 days (Figure 6).

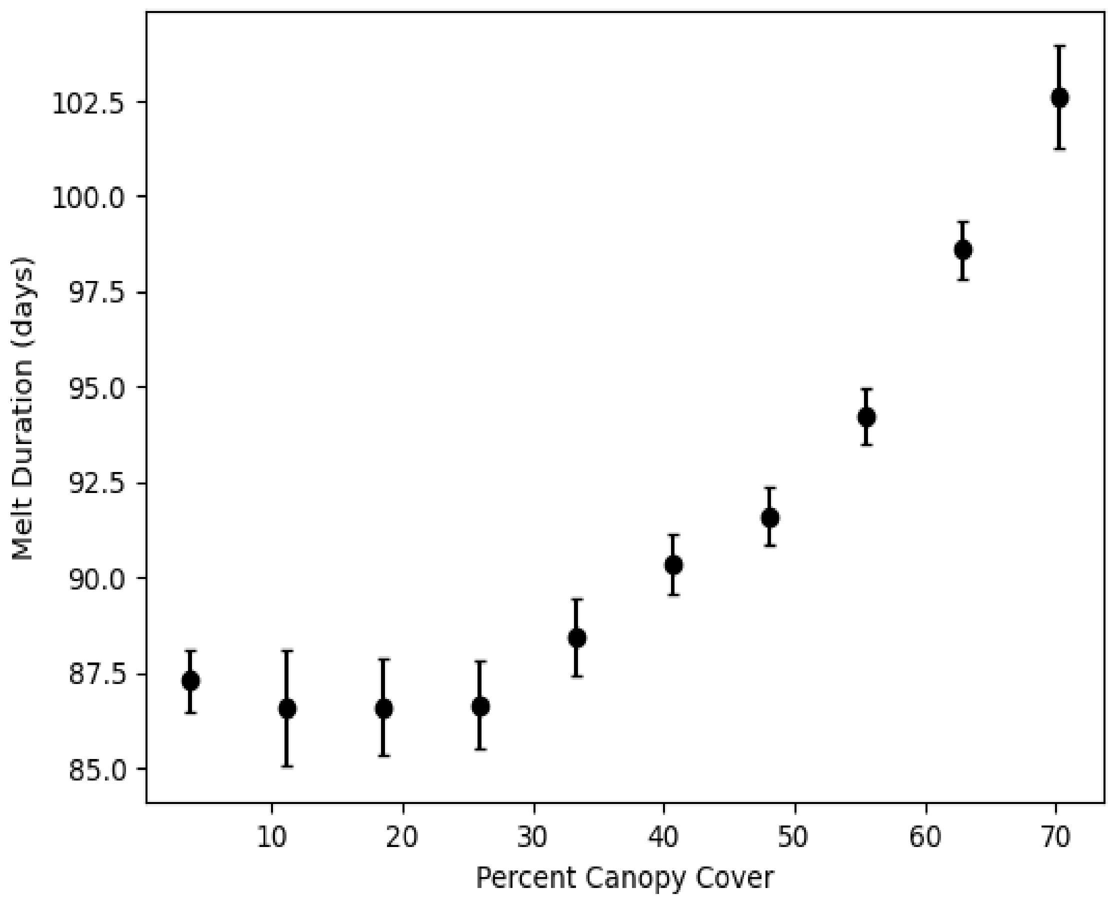

Figure 5. Binned scatter plot comparing percent canopy cover and melt duration. (n = 6290). Percent canopy cover data was divided into 10 equal intervals. Average melt duration was calculated for each bin and plotted as points with corresponding 95% confidence intervals, represented by error bars. The range of values within the error bars are 95% likely to contain the true average peak SWE value.

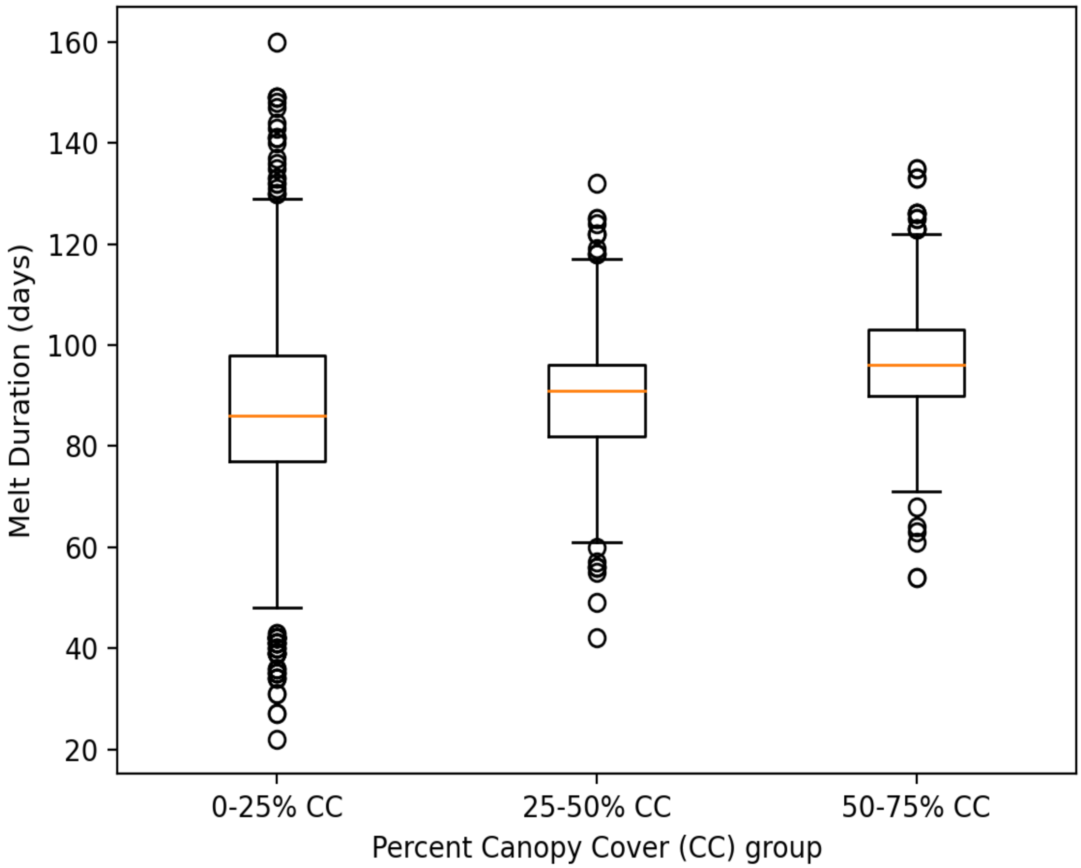

Figure 6. Comparison of melt duration between low (0-25%), medium (25-50%), and high (50-75%) canopy cover groups. The box-and-whisker plot summarizes group differences in average melt duration. The orange line in each box is the median melt duration value, while the top and bottom edges of the box mark the upper and lower quartiles, respectively. The top whisker represents the upper 25% of data, while the bottom whisker represents the lower 25% of data. Data outside the whiskers are outliers.

There was a statistically significant difference in melt duration between canopy cover groups as determined by one-way ANOVA ($p < .001$). A Games Howell post hoc test revealed that melt duration was statistically significantly higher for 50-75% canopy cover compared to the 0-25% ($p < .001$) and 25-50% ($p < .001$) categories (Table A4). As a result, I rejected the null hypothesis that there are no statistically significant differences between canopy cover groups.

Effect of elevation, northness, and slope

The Pearson correlation tests showed that all three topographic variables were correlated with melt duration with a significance under $p = .001$, but only elevation and northness were correlated with peak SWE (Table 5). The results indicated that there was a statistically significant relationship between topographic factors (i.e. elevation, northness, and slope) and melt duration, so I rejected the null hypothesis. Looking at peak SWE, there was a statistically significant relationship with elevation and northness, but not for slope. Therefore, I rejected the null hypothesis for elevation and northness and accepted the null hypothesis for slope.

Table 5. Summary of Pearson correlation analysis and effect size of topographic variables. Canopy cover was included in the regression analysis because it improved the predictive capabilities of the models. R values marked with an asterisk indicate a significance under p = .001. The effect size, or influence of a predictor variable, increases with the magnitude of beta values.

Variable	Peak SWE	Melt duration
Percent canopy cover	r = -.081 * β = .003	r = .263 * β = .679
Elevation	r = .314 * β = .399	r = .390 * β = .778
Northness	r = .336 * β = .353	r = .339 * β = .242
Slope	r = -.004 β = -.128	r = .044 * β = .057

Using canopy cover, elevation, northness, and slope as predictor variables, the linear regression model explained 24% of the variation in peak SWE and 56% of the variation in melt duration (Figure 6). Elevation and northness had comparable standardized beta coefficients and accounted for roughly 3 times more of the variation in peak SWE than slope and canopy cover combined, indicating that elevation and northness demonstrated the greatest total effect on peak SWE (Table 5). Melt duration was principally influenced by elevation and canopy cover, with less significant but non-negligible contributions from northness.

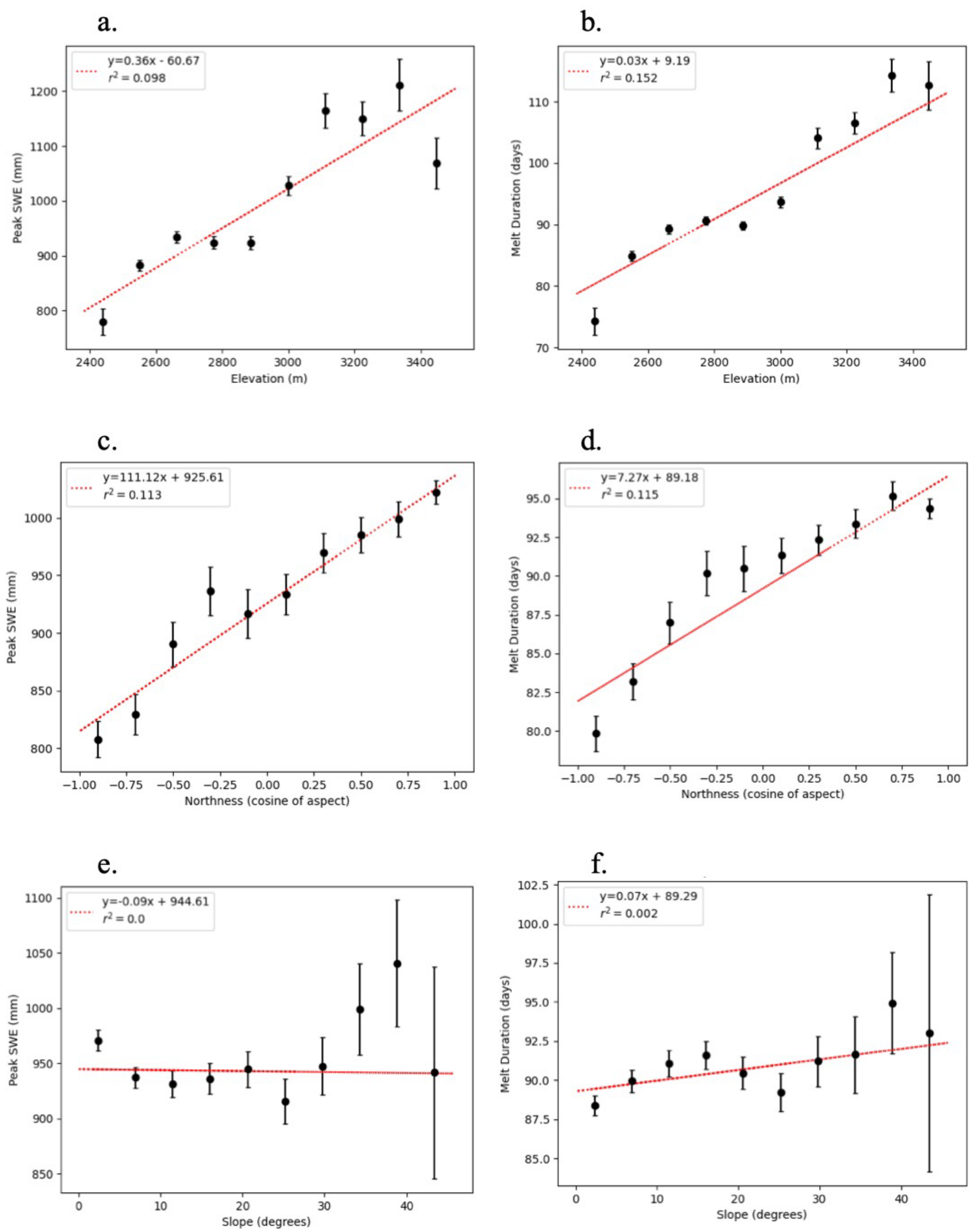

Figure 7. Regression plots highlighting the influence of topographic variables on peak SWE and melt duration. Graphs a., c., and e. show linear regression line equations and coefficients of determination (r^2) between peak SWE and elevation, northness, and slope, respectively. Graphs b., d., and f. show linear regression line equations and coefficients of determination (r^2) between melt duration and elevation, northness, and slope, respectively. r^2 values indicate the amount of variation in the dependent variable explained by a predictor variable.

DISCUSSION

Climate change poses a serious threat to California's water resources as temperatures rise and severe droughts become more prevalent, causing the demand for water to increase while simultaneously limiting the supply. This study aimed to find the amount of canopy cover that resulted in the greatest peak SWE and melt duration, with the larger goal of informing California forest management practices to mitigate the effects of climate change. The results indicate a negative relationship between canopy cover and peak SWE when canopy cover is under 50%; peak SWE increased with canopy cover above 50%, likely due to high snowfall events reducing the effectiveness of canopy interception. Melt duration showed a positive relationship with canopy cover, where areas with high canopy cover retained snow longer than low coverage. In addition to canopy cover, topographic variables like elevation, northness, and slope had a significant impact on snowpack processes. The results suggest that a forest structure consisting of high canopy cover with pockets of open area will optimize benefits to both snow accumulation and retention. This implies that utilizing vegetation treatment techniques to replicate this forest structure will increase snowpack volume and reduce ablation, but the effectiveness may be spatially variable due to terrain effects.

Maximizing snow water equivalent

Peak SWE was maximal in the 0-25% canopy cover group in the Owens River Headwaters Wilderness study site, accumulating 13% more snow than the medium cover group and 1% more than the high cover group. I found a weak negative relationship between canopy cover and peak SWE, supporting the findings from the meta-analysis by Varhola et al. (2010) that forested regions typically accumulate less snow compared to open areas. Although my results are statistically significant, the correlation coefficient is much weaker than the results of Varhola et al., which show an r value of -0.76 between canopy cover and snow accumulation. Previous research in the Sierra Nevada using LiDAR data found a strong linear increase in snow depth with decreasing canopy cover (Zheng et al. 2016). Similar studies in coniferous ecosystems reported up to 40% increases in SWE in open areas compared to forested locations (D'Eon 2004; Winkler 2005). My results showed a linear decrease in peak SWE until canopy cover reached roughly 45% where the trend reversed and peak SWE began to increase with canopy cover. I hypothesize that this contradictory finding is due to a shift in the energy balance at 45% canopy cover and above average precipitation during the 2011 water year. Zheng et al. (2018) studied the impact of canopy cover on snow accumulation at multiple locations across the Sierra Nevada over multiple water years, and found that the effect of canopy cover can be weakened by heavy snowfall. The Sierra Nevada snowpack volume during the 2011 water year was one of the largest on record at 156% above the normal average, which could explain the unexpectedly similar peak SWE values between the low and high canopy cover groups. Snow accumulation decreased with canopy cover as expected, but because of large storm events, the effectiveness of canopy interception of snow reduced significantly above 45% canopy cover. As a result, areas of high canopy cover accumulated more snow than usual while still receiving the additional benefit of increased protection from wind and solar radiation, potentially explaining the sharp linear increase in peak SWE between 50 and 75% canopy cover. Overall, the results are consistent with the existing literature indicating that clearings and low canopy cover areas accumulate the most snow on average, even during an abnormally snowy season. This supports the hypothesis that reducing canopy cover through silvicultural techniques (i.e. mechanical thinning and prescribed burns) can increase water resources during melt season, and the effects of treatment are likely to be more profound during normal or drought conditions.

Maximizing melt duration

Melt duration was maximal in the 50-75% canopy cover group in the Owens River Headwaters Wilderness. Percent canopy cover had a moderate positive relationship with melt duration, where areas with high canopy cover were more effective in retaining snow. The meta-analysis by Varhola et al. (2010) found a strong negative correlation ($r = -.85$) between canopy cover and ablation. So, as forest cover increases, less snow is lost to ablation and melt duration increases. Generally, my results support the findings of other snowpack studies that show slower melt rates in forested areas due to the trees' ability to reduce wind speed and provide shade. Lundquist et al. (2013) studied snow melt times around the world and found that warm winter environments with mean winter temperatures greater than -1℃ typically retain snow longer in open areas, while environments with mean winter temperatures less than -6 ℃ usually retain snow longer in forested regions. The Sierra Nevada is a warm winter environment, meaning it has potential for snow to last longer in clearings. However, this trend did not hold true in the Owens River Headwaters Wilderness.

I hypothesize that melt duration increased with canopy cover due to uncharacteristically low winter temperatures caused by anomalies in atmospheric circulation patterns. During the 2011 water year, the Sierra Nevada experienced colder winter temperatures because of La Niña conditions, a phenomenon that occurs every three to five years as a result of reduced sea-surface temperatures over the Pacific. The cooling effect was amplified by the Arctic Oscillation and Pacific North American Teleconnection both being in their negative phase, decreasing air temperature by almost 2℃ on average, nearly three times more than typical La Niña events (Guan et al. 2013). The extreme weather during the 2011 water year may have lowered air temperatures under the -1°C winter temperature threshold described by Lundquist et al. (2013), altering the forest energy budget to favor the retention of sub-canopy snow. This hypothesis warrants further investigation and presents an opportunity to improve upon this study by including meteorological measurements and comparing the 2011 melt duration values with those representative of normal conditions and periods of drought. Considering the abnormal circumstances, it is difficult to recommend an optimal canopy cover with regard to extending melt duration without knowledge of snowmelt dynamics during periods of average weather conditions. Certainly, the evidence suggests that during cold winters with above average precipitation, dense forests provide substantial benefits to the snowpack by decreasing melt rates, extending melt duration by more than two weeks compared to open areas. Therefore, I recommend preserving existing areas of high canopy cover between 50 and 75% coverage in order to extend melt duration, but this suggestion only applies to conditions similar to those witnessed during the 2011 water year. Additional research examining melt processes in the Eastern Sierra Nevada is necessary before any forest modification treatments occur.

Optimal terrain features

Among the three topographic variables analyzed in this study, elevation had the greatest overall importance to the snowpack. This result was expected; it is well documented that elevation has a strong linear relationship with snow accumulation and retention (Jost et al. 2007, Zheng et al. 2016, Kirchner et al. 2014). Research from the UCLA Center for Climate Science (2018) found that locations between 5000-8000 feet (1500-2500 meters) are most susceptible to the effects of climate change because they will suffer the greatest increases in temperature. Consequently, snow coverage will decrease, exposing the darker ground underneath and causing a positive albedo feedback loop in which temperatures and melt rates will be accelerated even more (Reich et al. 2018). The Owens River Headwaters Wilderness ranges from 2300-3600 meters, so concentrating forest thinning operations at the lower elevations will have the greatest benefit mitigating against climate change.

Northness also had a significant effect on the snowpack. Northness values closest to 1 resulted in the most snow accumulation and retention, with almost 30% more peak SWE than southern aspects and two weeks longer melt time. This result is in agreement with other snowpack studies in the northern hemisphere, with north-facing slopes receiving less solar radiation on average than east-, west-, or south-facing slopes, corresponding to greater snow accumulation and reduced ablation (Lopez- Moreno et al. 2014, Duyar 2018). Thus, forest thinning operation in the Owens River Headwaters Wilderness can be optimized by focusing treatment on north facing slopes.

Lastly, slope had the weakest effect on both peak SWE and melt duration among the compared to elevation and aspect. There was no discernible relationship between slope and peak SWE from the linear regression analysis; slope and melt duration were very weakly positively correlated. In addition, the variability in peak SWE and melt duration increased considerably at higher slopes. This contradicts previous research in the Sierra Nevada, which found greater variability in snow accumulation on gentle, flat surfaces, and increased melt rates at higher slopes (Anderson et al. 1958). The only result in agreement with Anderson et al. (1958) was the lack of an association between slope and peak SWE. Bloschl and Kirnbauer (1992) examined the effect of slope in the Austrian Alps and observed a fairly even distribution of snow under a 35% grade, which steadily decreased until becoming nearly barren of snow at 65% grade. Considering that slope in the Owens River Headwaters Wilderness never exceeds 45 degrees, it is likely that slope had a negligible effect on snow accumulation. Overall, the influence of slope on snow accumulation and melt duration is inconclusive because of weak or nonexistent linear relationships between variables as well as inconsistencies with previous studies.

Synthesis of results

In order to create a cohesive forest management plan to maximize snow retention, canopy cover and topography should be considered together. Open areas with no canopy cover resulted in the most snow accumulation, while the 50-75% cover group had the longest melt duration. It is unrealistic to designate a single percentage value as the optimal amount of canopy, i.e. stating that 40% canopy cover is ideal because it lies in the middle ground between benefits to snow accumulation and benefits to retention, and therefore the entire forest should have exactly 40% canopy cover. The evidence from 2011 data points to an optimal forest structure characterized by a combination of dense, high canopy cover forest with pockets of open clearings. The high canopy cover forest offer protection to the clearings by blocking solar radiation and reducing wind speed, allowing for enhanced snow retention. The open areas will more effectively accumulate snow without interference from canopy interception. Snow accumulation and retention can be further optimized by concentrating thinning treatments to north-facing slopes between 2300 and 2500 meters where the impact of climate change is most severe.

Limitations and future directions

Although forest thinning is usually used as a method to prevent catastrophic wildfires by reducing fuel loads, my research shows that thinning practices have implications for water resource management. A forest management study which links hydrology and fire ecology into a single, synthesized approach to optimize benefits by reducing fire severity and maximizing meltwater would be invaluable, especially in drought-prone areas like the Sierra Nevada. A research effort of this type must also account for the total impact of thinning operations on ecosystem processes by considering the effect on biodiversity, habitat alteration, forest health, etc.

Due to the vast array of variables that add complexity to hydrological processes, each watershed will have its own unique conditions and microclimates which are not generalizable across large scales. This is especially true for the results presented in this study, which were analyzed during an abnormally cold and wet winter season. At a minimum, this thesis can be used as a reference for comparison with other studies within the Mono Lake Basin of the Eastern Sierra Nevada (approximately 2300 - 3600 meters). Any forest management plan in this region must consider how the interaction between canopy cover and snowpack processes change with annual precipitation and temperature. My research fills the gap in knowledge for canopy-snowpack dynamics during cold winters with above average precipitation, but it is critical that this study is explored further to understand how hydrological processes are affected by variable weather conditions before any forest treatments are implemented.

Broader implications

Climate change presents serious challenges to California's water supply as the snowpack shrinks and melt season shortens, resulting in less available water during the agricultural growing season. The findings in this study inform forest management practices by providing valuable information for snowpack processes during a wet water year with above average precipitation. Any forest management regime with the goal of mitigating the adverse effects of climate change must carefully consider the year-to-year fluctuations in weather patterns and effect of topography before deciding on an optimal treatment. While silviculture will not solve all the problems that climate change presents, a forest management regime which adopts thinning practices may mitigate the consequences and add some stability to California's water resources.

ACKNOWLEDGMENTS

The progress I have made through the writing of this thesis would not have been possible without the support and guidance of the ESPM 175 instructors and peers. Patina Mendez, Leslie McGinnis, and Kyle Leathers were constant sources of compassion and encouragement despite the challenging circumstances of online learning this past year. I want to give special thanks to Kyle who was my primary instructor for grading, feedback, and questions during office hours and through email. My fellow environmental science classmate and roommate, Brian Price, was tremendously helpful by peer reviewing almost all of my work and offering his thoughtful advice. Lastly, I owe my sincerest thanks to my mentor Marianne Cowherd. From formulating my researching questions to helping revise my final draft, Marianne has been hugely involved over the last two semesters and I attribute much of my academic accomplishment in completing this thesis to her influence.

REFERENCES

Anderson, H.W., R.M Rice, and A.J. West. 1958. Snow in forest openings and forest stands. Proceeding Society of American Foresters. 46-50.

Bales, R.C., J.J. Battles, Y. Chen, M.H. Conklin, E. Holst, K.L. O'Hara., P. Saksa, and W. Stewart. 2011. Forests and water in the Sierra Nevada: Sierra Nevada watershed ecosystem enhancement project. Sierra Nevada Research Institute Report. 11.

Bloschl, G. and R. Kirnbauer. 1992. An analysis of snow cover patterns in a small alpine catchment. Hydrological Processes. 6: 99-109.

D'Eon, R. 2004. Snow depth as a function of canopy cover and other site attributes in a forested ungulate winter range in southeast British Columbia. Journal of Ecosystems and Management. 3(2).

Duyar, A. 2018. The effects of forest canopy cover and altitude on snow accumulation and melting in the upper watersheds. Fresenius Environmental Bulletin. 27: 9642-9649.

Ellis, C., J. Pomeroy, T. Brown, and J. MacDonald. 2010. Simulation of snow accumulation and melt in needleleaf forest environments. Hydrology and Earth System Sciences. 14: 925-940.

Guan, B., N.P Molotch, D.E Waliser, E.J. Fetzer, and P.J. Neiman. 2013. The 2010/2011 snow season in California's Sierra Nevada: role of atmospheric rivers and modes of large-scale variability. Water Resources Research. 49: 6731– 6743.

Hedstrom, N.R. and J.W. Pomeroy. 1998. Measurements and modelling of snow interception in the boreal forest. Hydrological Processes. 12(10-11):1611–1625.

Jost, G., M. Weiler, D. Gluns, and Y. Alila. 2007. The influence of forest and topography on snow and melt at the watershed-scale. Journal of Hydrology. 347:101-115.

Kapnick, S., and A. Hall. 2010: Observed climate-snowpack relationships in California and their implications for the future. Journal of Climate. 23:3446-3456.

Kattelmann, R.C., N.H. Berg, and J. Rector. 1983. The potential for increasing streamflow from Sierra Nevada watersheds. Journal of the American Water Resources Association. 19(3):395–402.

Kirchner, P., R. Bales, N. Molotch, J. Flanagan, and Q. Guo. 2014. LiDAR measurement of seasonal snow accumulation along an elevation gradient in the southern Sierra Nevada, California. Hydrology and Earth System Sciences Discussions. 11.

López-Moreno, J.I. and J. Latron. 2007. Influence of canopy density on snow distribution in a temperate mountain range. Hydrological Processes. 22(1):117–126.

López -Moreno, J.I., J. Revuelto, M. Gilaberte, E. Moran-Tejeda, M. Pons, E. Jover, P. Esteban, C. García and J.W. Pomeroy. 2014. The effect of slope aspect on the response of snowpack to climate warming in the Pyrenees. Theoretical and Applied Climatology. 117: 207-219.

Lundquist, J.D., J.R. Minder, P.J. Neiman and E. Sukovich. 2010. Relationships between barrier jet heights, orographic precipitation gradients, and streamflow in the northern Sierra Nevada. Journal of Hydrometeorology. 11(5): 1141-1156.

Lundquist, J.D., S. E. Dickerson-Lange, J. A. Lutz and N. C. Cristea. 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.

Ma, S., A. Concilio, B. Oakley, M. North and J. Chen. 2010. Spatial variability in microclimate in a mixed-conifer forest before and after thinning and burning treatments. Forest Ecology and Management. 259(5): 904–915.

Margulis, S.A., G. Cortés, M. Girotto and M. Durand. 2016. A Landsat-era Sierra Nevada snow reanalysis (1985–2015). Journal of Hydrometeorology. 17:1203–1221.

Margulis, S., M. Girotto, G. Cortés and M. Durand. 2015. A particle batch smoother approach to snow water equivalent estimation. Journal of Hydrometeorology. 16:1752-1772.

Musselman, K.N., N.P. Molotch, S.A. Margulis, P.B. Kirchner and R.C. Bales. 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.

Podolak, K., D. Edelson, S. Kruse, B. Aylward, M. Zimring and N. Wobbrock. 2015. Estimating the water supply benefits from forest restoration in the northern Sierra Nevada. An unpublished report of The Nature Conservancy prepared with ecosystem economics. San Francisco, CA.

Pomeroy, J.W., J. Parviainen, N. Hedstrom and D.M. Gray. 1998. Coupled modelling of forest snow interception and sublimation. Hydrological Processes. 12(15): 2317–2337.

QGIS Development Team. 2020. QGIS 3.16-Hannover. QGIS Geographic Information System. Open Source Geospatial Foundation Project.

Reich, K.D., N. Berg, D.B. Walton, M. Schwartz, F. Sun, X. Huang and A. Hall. 2018. Climate change in the Sierra Nevada: California's water future. UCLA Center for Climate Science.

Sommer, C.G., M. Lehning and R. Mott. 2015. Snow in a very steep rock face: accumulation and redistribution during and after a snowfall event. Frontiers in Earth Science. 3:73.

U.S. Geological Survey. 2014. NLCD 2011 USFS Percent Tree Canopy Cover Dataset.

U.S. Geological Survey. 2014. SRTM 1 Arc-second Digital Elevation Model.

Varhola, A., N.C. Coops, M. Weiler and R.D. Moore. 2010. Forest canopy effects on snow accumulation and ablation: an integrative review of empirical results. Journal of Hydrology. 392: 219–233.

Winkler, R.D., D.L. Spittlehouse and D.L. Golding. 2005. Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in southern British Columbia. Hydrological Processes. 19(1):51–62.

Zheng, Z., P.B. Kirchner and R.C. Bales. 2016. Topographic and vegetation effects on snow accumulation in the southern Sierra Nevada: a statistical summary from lidar data. The Cryosphere. 10:257–269.

Zheng, Z., Q. Ma, K. Qian and R. Bales. 2018. Canopy effects on snow accumulation: observations from lidar, canonical-view photos, and continuous ground measurements from sensor networks. Remote Sensing. 10(11):1769.

APPENDIX A: Descriptive SWE and Melt Duration Statistics with ANOVA Results

Table A1. Summary statistics of snow water equivalent (mm) for each canopy cover grouping.

Percent canopy cover group	N (sample size)	Mean	Std. deviation	Std. error	95% CI lower bound	95% CI upper bound	min	max
0-25%	2783	980.2	258.9	4.91	511.6	1552.4	141	2031
25-50%	1830	863.1	188.1	4.40	530	1266.5	366	1600
50-75%	1679	969.6	142.1	3.47	680	1241.1	412	1425
Total	6292	943.3	219.0	2.76	534.3	1431.7	141	2031

Table A2. Summary of ANOVA test results comparing peak SWE (mm) values between canopy cover groups

	Sum of squares	Degrees of freedom	Mean square	F	Significance (p value)
Between groups	16740472	2	8370236	184.645	<.001
Within groups	285044674	6288	45331		
Total	301785146	6290			

Table A3. Summary statistics of melt duration (days) for each canopy cover grouping.

Percent canopy cover group	N (sample size)	Mean	Std. deviation	Std. error	95% CI lower bound	95% CI upper bound	min	max
0-25%	2783	87.2	17.1	.324	53	119	22	160
25-50%	1830	89.4	10.3	.241	70	110	42	132
50-75%	1679	96.6	10.3	.251	79	118	54	135
Total	6292	90.2	14.2	.179	60	118	22	160

Table A4. Summary of ANOVA test results comparing melt duration between canopy cover groups.

	Sum of squares	Degrees of freedom	Mean square	F	Significance (p-value)
Between groups	94666.92	2	47333.46	252.026	<.001
Within groups	1180959.52	6288	187.812		
Total	1275626.44	6290			