TOWARDS A DECISION SUPPORT TOOL FOR UNDERSTANDING THE EFFECT OF FOREST THINNING ON THE SIERRA NEVADA SNOWPACK

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ABSTRACT

Snowmelt from the Sierra Nevada is a key water resource in the western US supporting economic development and ecological functions. Previous forest management practices have revealed that snowmelt volume depends on the complex interaction between changes to sublimation from canopy interception and net radiation at the snow surface. Despite decades of research, we lack insight into how to thin a forest to maximize snow accumulation and retention in complex topography. To better understand how different forest treatments might impact the snowpack, this study uses the Snow Physics and LiDAR Mapping (SnowPALM) model to simulate snowpack changes under a virtual forest thinning scenario over two mountainous watersheds at the west shore of Lake Tahoe, California. SnowPALM uses information about canopy density and height from lidar data to simulate tree-scale snow processes at 1-meter resolution. Questions addressed in this research are: what type of forest thinning are the most efficient to increase snow accumulation and melt volume, where do they have the largest impact, and what mechanism are driving these impacts? Simulations from this study will be used to produce a decision support tool for stakeholders, forest managers and policy makers at the west shore of Lake Tahoe.
(KEYWORDS: snow hydrology, forest thinning, LiDAR, Lake Tahoe)

INTRODUCTION

Warmer temperatures in the Sierra Nevada are shortening the snow accumulation season, increasing the frequency of mid-winter snowmelt events and producing earlier snowmelt runoff (Mote et al., 2018; Musselman et al., 2017), having a significant ecological (e.g. forest and health) and economic (e.g. agriculture and hydropower) impact. Forest removal practices can counteract the effect of climate change on the snowpack as more snow is expected in open sites due to a reduction in canopy interception of snowfall and sublimation. However, there are other physical processes that can play a significant role, such as changes to blowing snow redistribution, solar exposure and turbulent fluxes. Forest removal experiments and comparative studies between canopy clearing and forested sites have shown large variability in snow accumulation and melt across climate zones (Golding and Swanson, 1986; Pomeroy et al., 2002; Toews and Gluns, 1986; Troendle and Leaf, 1980; Woods et al., 2006). The size of the forest gap plays a major role determining the impact of forest removal on snow retention (Troendle and Leaf, 1980), large forest gaps may lose snow through wind redistribution in cold and windy sites, and can also increase mid-winter melt rates through increasing solar exposure.

Determining the impact that forest thinning will have on snowpack requires either empirical studies to compare the snowpack for thinned vs. unthinned areas or modeling studies that simulate the effect of the forest thinning. Both approaches have had limitations as empirical forest removal studies tend to have relatively small domains (e.g. Anderson and Gleason, 1960) due to operational costs, and modelling studies typically fail to represent the spatial heterogeneity of forest cover and instead use spatially-averaged parameters to represent snow-forest interactions. However, increasing aerial LiDAR availability, computational power and better representations of small-scale snow-forest interactions (Moeser et al., 2016, 2015; Musselman et al., 2015; Pomeroy et al., 2002), have improved our ability to represent and simulate these processes. Models at high spatial resolution (e.g. 1 m) allow a more robust representation of the spatially heterogeneous effect of forest canopy on snow accumulation and melt, which can improve model performance and reduce uncertainty in simulations (Broxton et al., 2015; Moeser et al., 2015).

The purpose of this research is to understand the effect of forest thinning on snow accumulation and melt in two mountainous and forested watersheds in the Lake Tahoe area of the Sierra Nevada, identifying the type of forest thinning that is the most efficient and the physical mechanisms driving these changes. We use spatially explicit (1 m)

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snow modelling of snowpack changes that occur under a virtual forest thinning scenario to understand the impact of local topography (e.g. elevation, slope and aspect), climate (e.g. high vs. low elevation) and existing vegetation variability on changes to the snowpack. This work is expected to be the first step into developing a decision support tool for predicting the effect of forest thinning on the snowpack of other watersheds in the Sierra Nevada.

STUDY SITE AND DATA

Two mountainous watersheds at the west shore of Lake Tahoe, California, were chosen for this study (Figure 1), Ward Creek (24.9 km^2) and Blackwood Creek (28.9 km^2). Elevation ranges from roughly 1,900 m a.s.l. to 2,700 m a.s.l. At lower elevations near the shore of Lake Tahoe, there are gentle slopes with tall and dense forests, and at higher elevations, there is much steeper topography with sparser vegetation cover. These two watersheds were selected because LiDAR data are available, providing high resolution (1-m) maps of vegetation height and density (Xu et al., 2018), which are required for SnowPALM, there is a SNOTEL station that can be used for model validation, and they have large topographic, climatic and forest (e.g. density and height) variability. The meteorological data used in this study are from the North American Land Data Assimilation System (NLDAS), which provides hourly precipitation, air temperature, wind speed, air pressure, downward shortwave and longwave radiation and specific humidity at 1/8 of degree spatial resolution.

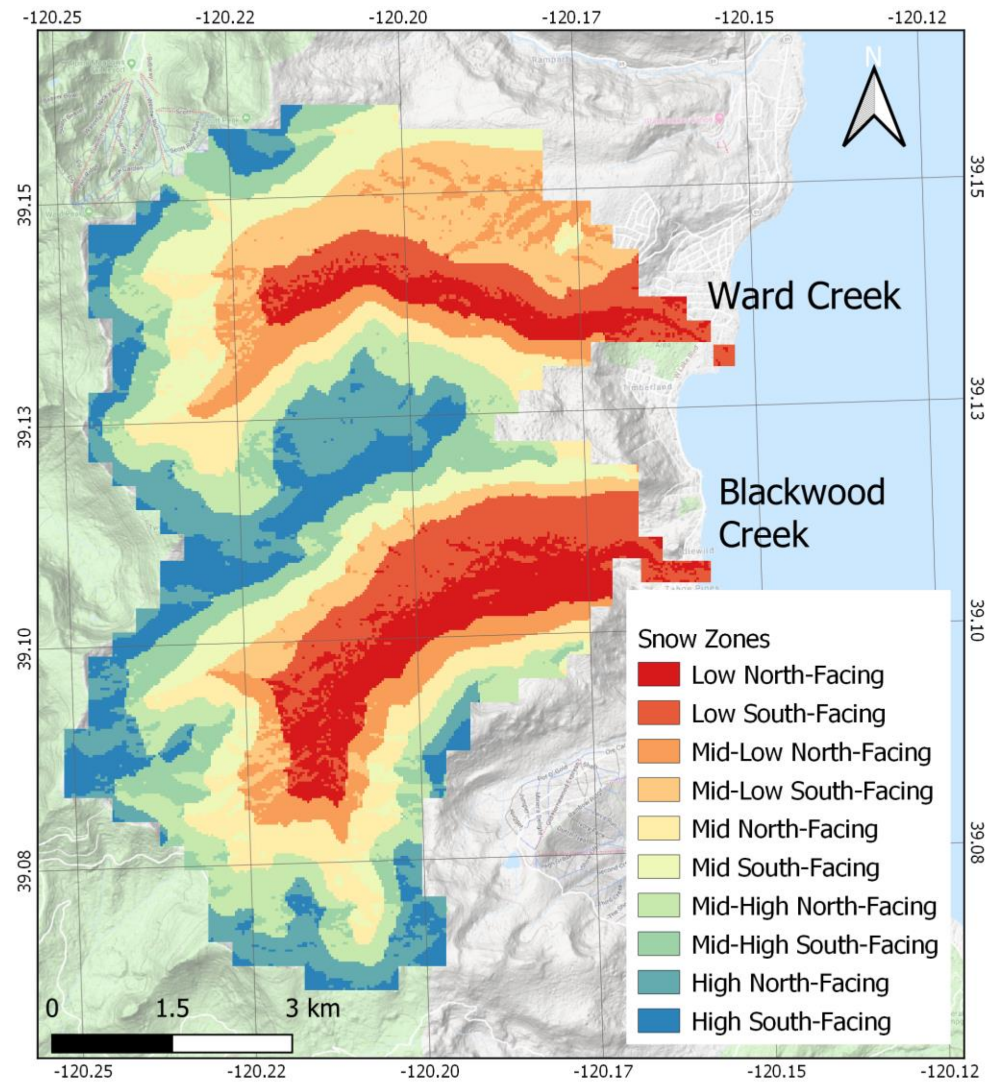

Figure 1. Modelling domain at the west shore of Lake Tahoe, California. Snow zones are defined by elevation bands and aspect.

MODELLING

We use the Snowpack Physics and Lidar Mapping (SnowPALM; Broxton et al., 2015) model to simulate snowpack across these watersheds under a virtual forest thinning scenario. SnowPALM simulates snow-forest interactions and other snow processes at one-meter spatial resolution using an explicit representation of vegetation structure (typically from airborne LiDAR maps). It includes a snowpack layer to compute the energy and mass balance whose skin temperature is calculated separately through an energy balance between net radiation, sensible and latent heat, and heat conduction to the middle of the snowpack, and a soil layer to compute ground heat exchange. Other processes included in SnowPALM are: wind distribution of snowfall, canopy interception of rainfall/snowfall and evaporation/sublimation, canopy unloading of rain/snow, attenuation of longwave and shortwave radiation by the forest canopy, and albedo decay as a function of time, and the liquid water content in the snowpack. Further details about the model can be found in Broxton et al., 2015.

First SnowPALM was run over Ward Creek and Blackwood Creek for a normal (2015-2016) and a wet water year (2016-2017) using existing vegetation structure. Then, a virtual forest thinning scenario (whereby trees that are less than 10 m tall) was performed to assess the impact of forest thinning on snow accumulation and melt in this environment. These model results are analyzed separately for areas with distinctive snow regimes (i.e. patterns of snow accumulation and melt), which are referred to as Snow Zones that include five elevation bands, defined using every 20th percentile of elevation, on north and south facing slopes, as shown in Figure 1.

RESULTS

After the virtual forest thinning, changes to peak snow water equivalent (SWE) and total melt volume were highly spatially heterogeneous. Figure 2 shows a subdomain (roughly 250m x 250m), located at the lower north facing Snow Zone, as an example of the effect of the <10m forest thinning on existing forest structure (upper panels) and the spatially variable response to peak SWE and melt volume (lower panels) for the normal water year (2015-2016). This example demonstrates that both changes in peak SWE and melt volume (thinning scenario minus historical run) are highly correlated and closely follow changes in vegetation structure. Increases in snow accumulation and melt are largest near existing forest patches that remain relatively sheltered from solar radiation even after surrounding vegetation was removed. Conversely, when vegetation is removed from previously exposed (high solar radiation) areas, there is either no impact or a small decrease to peak SWE and total melt volume.

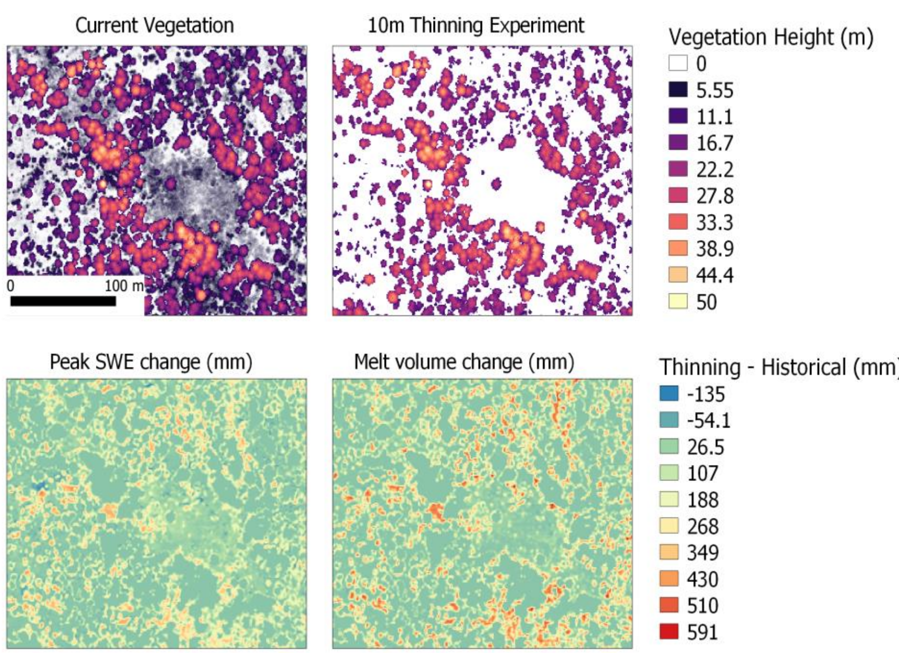

Figure 2. Subdomain sample of the virtual thinning scenario and the respective change in peak snow water equivalent and total melt volume for the 2015-2016 water year

Vegetation changes due to the thinning experiment have a distinct effect across Snow Zones, largely because of the differences in the existing vegetation structure between lower and higher elevations (Table 1). Vegetation at lower elevations is typically composed of denser and taller trees, as opposed to hillslopes at higher elevations; therefore, larger changes to vegetation height and density were found at lower elevations (>15%). Table 1 also shows mean changes to peak SWE and total melt volume across snow zones and for the water year 2015 (normal year) and 2016 (wet year). Changes in both peak SWE and melt volume show larger increases at lower elevations than at higher elevations. Peak SWE at the low elevation and north-facing snow zone (largest change) increased by 64 and 82 mm, or 17 and 6% with respect to the control run, for the water years 2015-2016 and 2016-2017, respectively, whereas at the high elevation and south-facing snow zone (smallest change) it increased by 40 and 35 mm, or 4 and 2%, for the two water years, respectively. Similarly, changes to total melt volume at the low elevation and north-facing Snow Zone shows the largest increase at 90 and 111 mm, or 9 and 5%, for the 2015-2016 and 2016-2017 water years, respectively, whereas at the high elevation and south-facing slope it shows the smallest change at 37 and 39 mm, or 2 and 1%, respectively.

Table 1. Changes to average vegetation height (m), vegetation density (%), peak SWE (mm) and melt volume (mm) across snow zones.

Snow Zone	Δ Canopy Height	Δ Canopy Density	Δ Peak SWE 2015-2016	Δ Peak SWE 2016-2017	Δ Melt Volume 2015-2016	Δ Melt Volume 2016-2017
Low N	-1.7	-20	64	82	90	111
Low S	-1.4	-15	37	67	74	89
Mid-Low N	-1.4	-15	56	62	62	78
Mid-Low S	-1.3	-14	44	59	64	77
Mid N	-1.2	-13	49	52	49	62
Mid S	-1.2	-12	48	53	56	66
Mid-High N	-1.0	-11	42	41	42	51
Mid-High S	-1.0	-10	44	40	43	45
High N	-1.0	-11	42	41	41	48
High S	-0.9	-9	40	35	37	39

DISCUSSION AND CONCLUSIONS

These preliminary results demonstrate that the effect of forest thinning on snow accumulation and melt is complex and spatially heterogeneous, as it not only depends on the local interaction between snow, attenuation of solar radiation, and interception by the overhead forest canopy, but also on changes to nearby forest cover and height, which can provide significant shelter from solar radiation and wind. At the Snow Zone scale, larger absolute increases in both peak SWE and melt volume were found for the wet (2016-2017) water year (Table 1); however, relative changes were larger during the normal (2015-2016) water year, suggesting that more snowfall does not necessarily produce a corresponding increase in sublimation from canopy interception, likely due to the limited interception capacity of trees and different meteorological conditions (i.e. air temperature and humidity) between water years. Average changes to the snowpack over the Snow Zones also showed significant spatial variability, with the lower and north facing Snow Zones having the largest increase to both peak SWE and melt volume (17% and 9%, respectively) in the normal (2015-2016) water year. Conversely, higher and south facing Snow Zones showed the lowest increase in peak SWE and melt volume (4% and 3%, respectively) for the same water year. This pattern is likely explained by the following three reasons: (1) lower elevations generally have a denser forest than higher elevations, resulting in a larger removal under the thinning scenario and, therefore, a larger average increase in peak SWE and melt (2) lower elevation areas remain more sheltered than hillslopes at higher elevations because of the taller trees; and (3) hillslopes at higher elevation are steeper and, therefore, more sensitive to increase solar exposure after forest thinning.

Next steps of this research include extending the modelling domain to two adjacent watersheds to increase the spatial representativeness of these results, including a more severe thinning scenario that will further change the existing structure of the forest, investigating in more detail the spatial and temporal variability of changes to the snowpack and the characteristics of the tree stands that are most sensitive to forest removal. Results from these analyses will be incorporated in a machine learning algorithm to extrapolate these results to other watersheds in the Lake Tahoe Basin.

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