THE EFFECT OF FOREST STRUCTURE ON SNOWPACK ALONG ARIZONA'S MOGOLLON RIM

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EXTENDED ABSTRACT

Across the Western US, snowmelt, particularly from mountain forests can contribute more than 75% of surface water resources. This is true even in the semiarid southwestern US, where 80-90% of annual runoff can occur during the late winter and spring. Snowpacks in this region, which are already shallower and temporally more variable than snowpacks of wetter and cooler climates further north, are particularly vulnerable to climatic changes such as regional warming and drought.

Changes in forest structure have the potential to exacerbate or mitigate snowpack changes brought about by these climatic changes. Forest structure exerts a strong control on snowpack because of the interplay of various factors such as interception and shading from the trees. For example, interception reduces the amount of snow reaching the ground, while shading by terrain and/or forest vegetation protects the snowpack on the ground from sublimation loss (e.g. Musselman et al., 2008; Rinehart et al., 2008, Veatch et al., 2009; Figure 1). For example, this tradeoff means that despite causing a decrease in interception, forest removal may result in equal or reduced SWE (Harpold et al., 2014; Biederman et al., 2014). Furthermore, the relative importance of these factors depends on climate and topography. For example, steep north facing slopes, which are already shaded may be more sensitive to changes in interception than to forest shading, while on sunny south facing slopes, shading from nearby trees can be important for retaining snowpack.

Figure 1. Image at one of our study sites depicting deep snow in areas shaded by trees and shallow / absent snow in sunnier areas, particularly on the warm sides of canopy stands.

While there has been extensive work to understand the role of forest structure at high elevations with persistent seasonal snowpacks, the goal of this study is to understand how forest structure interacts with climate and topography to regulate the thin, variable, and often ephemeral snowpacks of the Southwest. Specifically, we 1) examine the spatial variability of snow, as it relates to variable canopy structure using LiDAR-based snow data from Arizona, and 2) determine through comparison of LiDAR data with model snow simulations assuming no vegetation whether forest cover increases or decreases snowpack in different topographies and climates in the area.

In this study, we use LiDAR maps of snow, forest structure and terrain, synchronous ground observations, and process based and machine learning models to understand the impact of forest structure on snowpack within the economically important Salt and Verde watersheds in Arizona. Two LiDAR boxes (each having an area of ~100 km^2), capture snowpack for a mid-elevation ponderosa pine forest, and a high-elevation mixed conifer forest with montane meadows. In this study, we focus on airborne LiDAR surveys for each box in February, 2017 representing mid-winter snow conditions. These surveys are accompanied by ground surveys of snow depth (n~4000) and snow density (n~300) at seven intensively studied sites within the LiDAR domains, capturing a wide range of variables expected to control snowpack: elevation, slope, aspect, forest density, and forest geometry. Ground measurements of snow depth are used to correct small errors in the LiDAR snow depths, and artificial neural network (ANN) machine learning of the snow density measurements is used to create maps of snow density, which are combined with the LiDAR snow depth maps to produce maps of SWE.

To understand the impact of forest structure on snowpack across the LiDAR domains, we use a 1 meter energy balance model called SnowPALM (Broxton et al., 2015), along with machine learning of the LiDAR and ANN-based SWE maps to predict how radiation and snowpack are affected by forest canopy. Through this modeling, we produce sub-canopy radiation maps for the LiDAR domains, as well as maps of what SWE would look like in the absence of any tree cover across the LiDAR domains. Differences between the observed snow amounts and modeled snow amounts assuming no trees indicate SWE differences caused by trees. These differences are examined in relation to tree cover percent and under canopy shading factor (which is calculated as one minus the under canopy solar forcing index computed by SnowPALM).
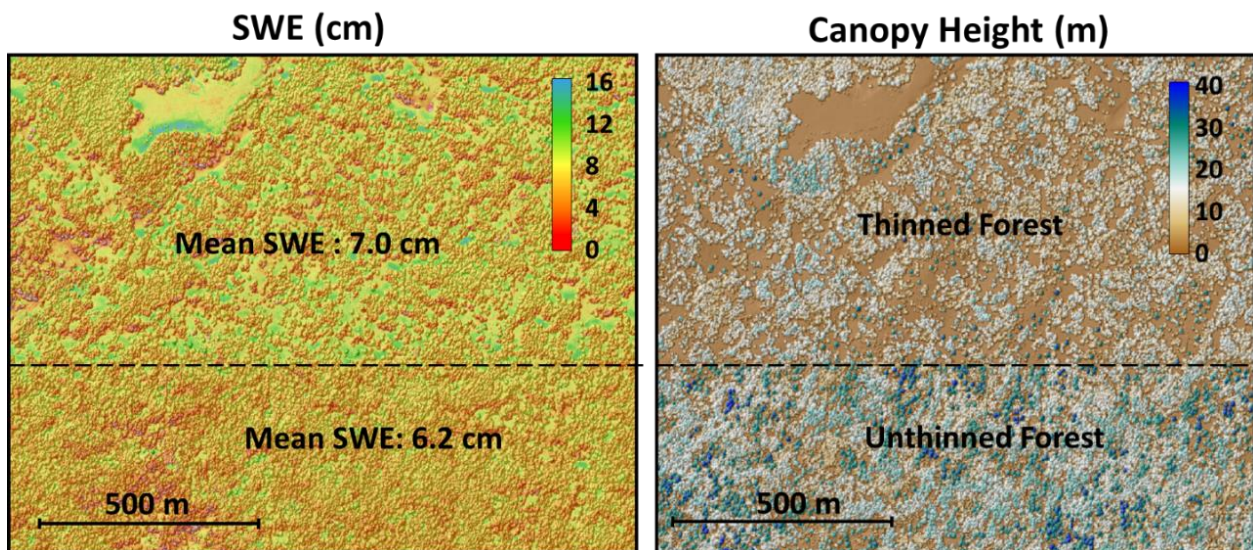

Figure 2. **Left:** SWE distribution across a managed forest boundary at a site with flat topography in the mid-elevation LiDAR box showing the average SWE in the thinned and unthinned parts of the image. **Right:** Canopy height for the area. Note the canopy hillshade effect on both maps to emphasize the locations of trees.

Snow distributions and amounts vary in forests with different canopy structure. As an example, Figure 2 shows maps of SWE for an area of the mid-elevation box where there is a pronounced boundary between a thinned and an unthinned ponderosa pine forest. The thinned forest has more gaps between the tree stands than the unthinned forest. In general, there is more snow in the thinned forest, in particular in the mid-sized forest gaps and on the shaded southern edges of large clearings. Less snow is found under tree canopy, on the exposed sunny sides

of tree stands, and in the middle of large clearings. These differences in snow amounts reflect differences in interception, and variable energy inputs in shaded vs non-shaded areas next to trees. Overall, SWE amounts in the thinned forest in this area are ~13% more than in the unthinned forest.
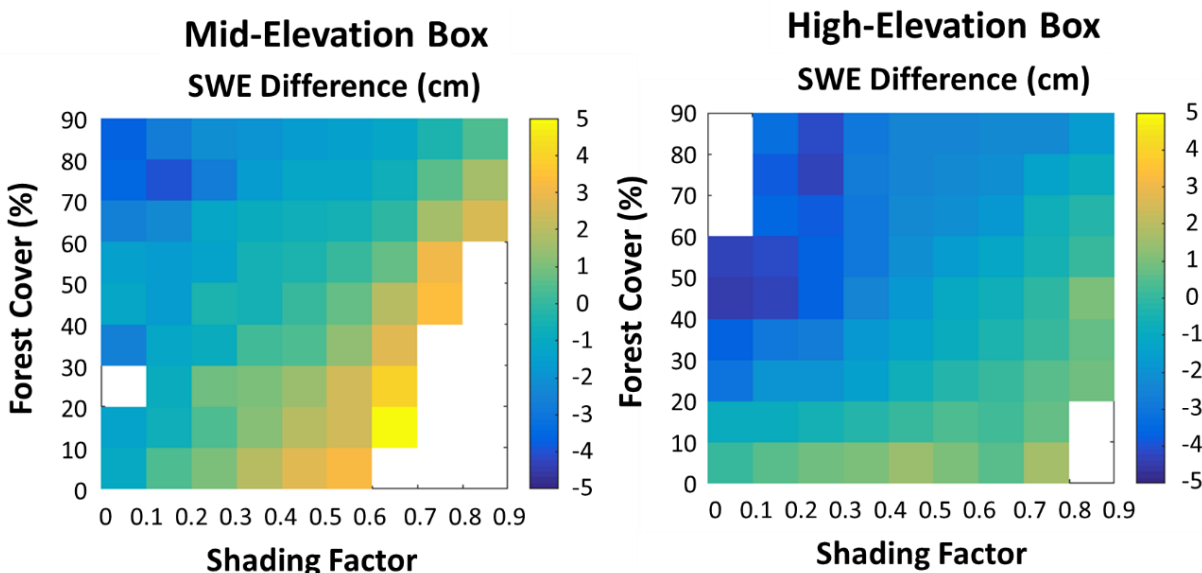

Figure 3. Observed minus bare earth SWE in different categories of forest cover and shading factor for the (**left**) mid-elevation and (**right**) high-elevation LiDAR boxes. Shading factor is calculated as one minus the sub-canopy solar forcing index.

The above example offers clues about the impact of forest structure on snowpack, but when looking across the entire LiDAR domains, we find that the interaction of treecover and shading leads to a net-positive or a net-negative SWE response to forest cover. Figure 3 shows that SWE is less, relative to unforested areas when the tree cover is high but the shading factor is relatively low. Conversely, areas with high amounts of shading tend to have more SWE than unforested areas, particularly at low-medium canopy cover. This effect is more pronounced in the mid-elevation LiDAR box. As a result of this interaction, the impact of forest structure on snowpack is not simple. Rather, it is different for different topographies and climates. For example, we find that forest cover doesn't seem to affect snowpack on south-facing aspects as much as it does for north-facing aspects. Furthermore, there were significant differences between its effects for the mid-elevation vs high-elevation LiDAR box. For example, on north facing slopes in the high-elevation box, SWE tends to decrease monotonically as canopy cover increases, while in the mid-elevation box, SWE increases for low-medium canopy cover and decreases for high canopy cover, suggesting the increased importance of forest shading, perhaps for retaining snowpack which is more easily lost in the warmer environment of the mid-elevation box.

(KEYWORDS: Airborne LiDAR, Modelling, Forest Structure, SWE, Arizona)

REFERENCES

Biederman, J. A., Brooks, P. D., Harpold, A. A., Gochis, D. J., Gutmann, E. , Reed, D. E., Pendall, E. and B. E. Ewers. 2014. Multiscale observations of snow accumulation and peak snowpack following widespread, insect-induced lodgepole pine mortality. *Ecohydrol.,* **7**: 150-162. doi:10.1002/eco.1342

Broxton, P. D., Harpold, A. A., Biederman, J. A., Troch, P. A., Molotch, N. P., and P. D. Brooks. 2015. Quantifying the effects of vegetation structure on snow accumulation and ablation in mixed-conifer forests. *Ecohydrol.,* **8**: 1073–1094. doi: 10.1002/eco.1565.

Harpold, A. A., Biederman, J. A., Condon, K. , Merino, M. , Korgaonkar, Y. , Nan, T. , Sloat, L. L., Ross, M. and P. D. Brooks. 2014. Changes in snow accumulation and ablation following the Las Conchas Forest Fire, New Mexico, USA. *Ecohydrol.*, **7**: 440-452. doi:10.1002/eco.1363

Musselman, K. N., Molotch, N. P. and P. D. Brooks. 2008. Effects of vegetation on snow accumulation and ablation in a mid-latitude sub-alpine forest. *Hydrol. Process.*, **22**: 2767-2776. doi:10.1002/hyp.7050

Rinehart, A. J., Vivoni, E. R. and P. D. Brooks. 2008. Effects of vegetation, albedo, and solar radiation sheltering on the distribution of snow in the Valles Caldera, New Mexico. *Ecohydrol.,* **1**: 253-270. doi:10.1002/eco.26

Veatch, W., Brooks, P. D., Gustafson, J. R. and N. P. Molotch. 2009. Quantifying the effects of forest canopy cover on net snow accumulation at a continental, mid-latitude site. *Ecohydrol.,* **2**: 115-128. doi:10.1002/eco.45