APPENDIX F

The Effects of Tree Thinning on Canopy Interception and Throughfall in the Sacramento Mountains

This document describes data analysis and interpretations by Ethan Mamer to assess the effects of tree thinning on canopy interception and throughfall.

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The Effects of Tree Thinning on Canopy Interception and Throughfall in the Sacramento Mountains

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Introduction

One of the goals when tree thinning was conducted in the Sacramento Mountains was to increase the water supply in a high mountain recharge area. The first obvious impact that tree thinning has on the water balance of the system is the reduced number of trees that are removing water from the system. A less obvious impact of tree thinning is the reduced canopy cover that would otherwise prevent rain from reaching the ground. This appendix will provide a more detailed examination of the effect that three thinning has on the potential for precipitation, in the form of rain and snow, to reach the forest floor.

Background:

Rain interception

Canopy interception (I) is defined here as the volume of precipitation that never reaches the ground, but is instead stored in the forest canopy and evaporates before reaching the forest floor. The portion of precipitation that makes it past the canopy to the ground is classified as throughfall (T). Understanding the properties of a forest's canopy that control interception and throughfall allows us to more accurately conduct water balance calculations, allowing us to estimate how much precipitation is available to recharge the local aquifers.

Rain storms, as they relate to the forest canopy, can be broken into two stages; a wetting, and saturated phase. During the initial wetting phase the only precipitation which makes it to the forest floor is rain that falls directly to the ground without touching the canopy, and is defined as direct throughfall (p). Rainfall that hits the canopy gradually builds up until the weight of more rain overcomes the surface tension holding the water on the leaves and branches. A tipping point is reached when the canopy is saturated, at which point water begins to drain off of the canopy. This is defined as the saturation point (Ps). Storms that overcome the saturation point have the potential to provide greater throughfall, and provide potential recharge.

Canopy structure plays the biggest role in determining potential throughfall. The canopy structure of forests composed of leafy (deciduous) trees change greatly throughout the year with the growing season. Pine (coniferous) trees, the primary trees present in the study area, have a more constant canopy density. By thinning the forest we have effectively reduced the canopy cover, and increased the potential throughfall.

Snow-melt Loss

Snow-melt loss works in a similar fashion as rain, however, there are numerous other factors that impact how much snow water equivalent (SWE) reaches the forest floor. Previous studies suggest that an even higher proportion of snow precipitation, compared with rain, can be intercepted by tree canopies and sublimated to the atmosphere if the events are small (Veatch et al., 2009). Wind, of course, can decrease the portion of snow that is intercepted by the canopy, however, it can also have the opposite effect. In a similar study on tree thinning conducted in Montana, the decrease in canopy was found to lead to an increase in wind speed and solar radiation. This, in turn, lead to an increase in sublimation, that offset the effect of interception reduction (Woods et al., 2006). Additionally, the aspect of the hill slope, (or the direction which the slope faces) was shown to have an effect on snow accumulation and melting. More snow accumulates on the northerly aspects (in the northern hemisphere) due to reduced melting and sublimation rates (Golding and Swanson, 1986). The hillslope also impacts snow available to melt, as result of down slope migration, and increased exposure to solar radiation at lower incident angles on the south facing slopes, leading to increased sublimation. This complicated system of variables makes modeling the effect tree thinning has on snow-melt loss very difficult to predict.

Methods:

Rain Interception:

Throughfall Collectors (TFC)

Rain throughfall was measured at five locations in the 3L watershed under the canopy in a forest comprised primarily of Douglas-Fir (Figure G1). Throughfall measurements, as well as gross precipitation measurements were collected between 2008 and 2015. Trough collection systems, similar to Navar et al. (1999a), were constructed to capture a more uniform representation of throughfall under a dense canopy. Each throughfall collector (TFC) consisted two PVC troughs, with a total area of 0.404m^2, that fed into a Novalynx (0.25 cm) tipping bucket (Figure G2). In 2008 an initial two throughfall TFCs were deployed. In 2011 an additional two TFC were deployed, and the original two were moved to gather data under different canopy covers. TFC 6 (SM-5113) was placed in the open near the weatherstation (SM-5004) to act as a control, while the other three were placed under different canopy densities. The percent canopy cover over the TFCs ranged from 40 to 89%, as determined by the remote sensing software Ecognition (Appendix D).

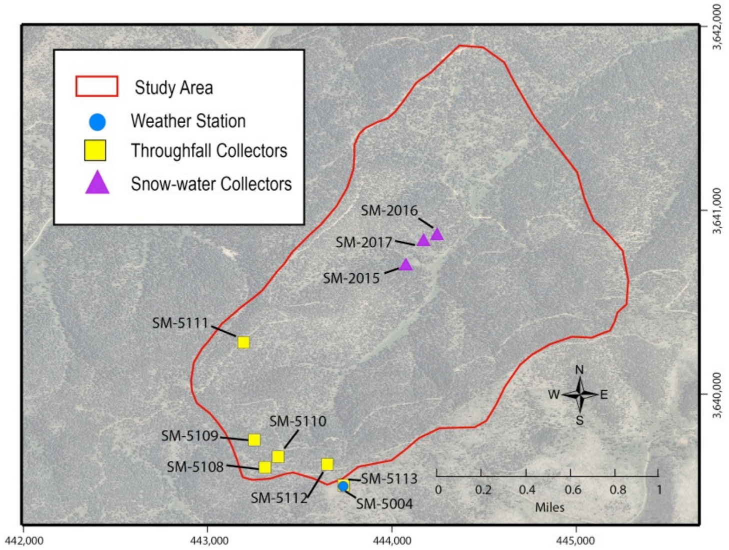

Figure G1: Location of sample sites and instrumentation in study area.

Figure G2: Photo of throughfall collection setup.

TFC Data Filtering

The hourly precipitation records from the TFC's and the weather station (SM-5004) in the clearing were compared, and filtered. First, all data ranging from November through February was removed from the TFC record for this analysis, as snowfall was analyzed separately. Individual storms are assumed to be separated by periods of drying which no precipitation was recorded at the weather station. A Matlab code was written to isolate storms separated by at least a 3 hour drying period. The hourly precipitation recorded during each isolated event were then summed and recorded.

TFC Data complications

Working with TFC troughs did present some challenges. The remote nature of the watershed restricted instrument maintenance and data collection to quarterly visits, which lead to complications concerning the reliability of the data. The purpose of the TFC was, of course, to capture rainfall under a tree canopy. Unfortunately, the TFC's also capture tree debris such as pine needles and leaves. When the collection troughs become clogged with debris the throughfall is not accurately recorded. Instead, the throughfall splashes off the debris, or is evaporated, leading to only a small prolonged trickle being recorded by the tipping bucket. Data had to be manually filtered to find erroneous patches.

Additional, the local elk population proved almost as destructive as bored teenagers, taking a perverse pleasure in knocking over the 'control' collection troughs (SM-5113) placed in the open field (Figure G3), resulting in limited usable data.

Figure G 3: Very bad elk!

TFC Regression Analysis for Rain Events

Regression analysis is based on a least square fitting of data, and can be used to determine several key parameters important to studying canopy interception. It has been commonly used since published by Horton (1919), and further refined by Klaasen et al. (1998) as a 'waterbox' concept. The method relies on two main assumptions: storms are separated by periods of dry, long enough to entirely dry the canopy, and canopy drainage is negligible aft the rain has stopped.

By comparing the precipitation records collected from the throughfall collectors T (mm), and the gross precipitation Pg (mm) from the weather station, we can learn a great deal about the forest canopy. To approximate several canopy dependent variables, past researchers have used linear regression based analysis. Interception, I (mm), is estimated by subtracting the measured throughfall from the gross precipitation record ($I = Pg - T$).

For each TFC location storms are partitioned into rainfall events that are either insufficient or sufficient to overcome the wetting phase. This saturation point is determined by first graphing smaller storms, fitting a line through the data and observing the R^2 value. Gradually larger storms are plotted until the R^2 value begins to decrease (Figure G4A). This tipping point is defined as the point of saturation, Ps (mm). Storms smaller than this value ($Pg<Ps$) are assumed to not be sufficient to saturate the canopy. One minus the slope of the line fit to interception vs gross precipitation for these smaller storms is an approximation of p, or the fraction of precipitation that reaches the forest floor directly through spaces in the canopy (Pypker et al., 2005).

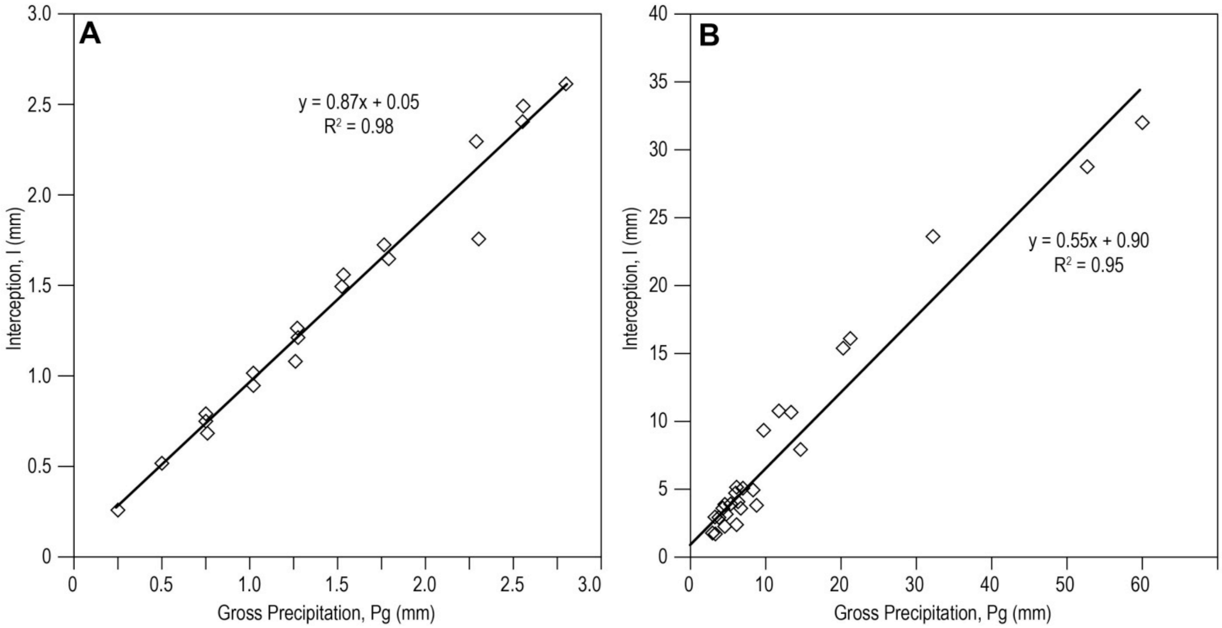

Figure G4: A) Storms less than the saturation point for a given location are plotted, and a line is fit through this data. One minus the slope of linear fit is the direct throughfall coefficient, p. B) Storms that exceed the saturation point, are plotted, the slope of this line is used as an approximation of the evaporation to rain rate ratio (E/R). **(SM-5110)**

Storms that exceed this saturation point (Pg>Ps) are assumed to have overcome the initial wetting phase, and precipitation is able to drip through the canopy. The slope of the linear regression fit to these larger storms is an approximation of the evaporation to rain rate ratio (E/R) (Figure G4B).

Canopy storage capacity is a tricky variable to determine, in part, because past research has not used the same definition of S. The discrepancy is accentuated by various direct and indirect methods for its estimation. Gash and Morton (1978) defined S as the minimum amount of water required to fill the canopy storage. Other estimates have defined it as the amount of water left on the canopy in a zero evaporation condition, following a large storm. In this report we will focus on the mean canopy Storage, , described as:

Though interception was already calculated directly from the raw data, it can be recalculated analytically using the following equation:

The y intercept for line plotted for storms greater than the saturation point (Pg>Ps) represents the mean storage capacity, (mm), for the canopy at the sampled location.

Snow-melt Loss:

Snow Melt Collectors

For the purpose of measuring snow water equivalent (SWE) that melts and reaches the ground we installed three snow melt collectors. The snow melt collectors we used were based on modified tipping buckets with large aluminum cones attached (Figure G5). The cones allowed us to sample a larger area with a limited number of instruments, increasing the area each tipping bucket sampled from 50.25 in^2 to 430.05 in^2. The tipping bucket was installed below the ground, allowing the cone to rest at ground level.

Figure G5: Installation of snow melt collectors. A tipping bucket rain gauge is modified and buried. The collection funnel is on the ground.

The three snow melt collectors (SNOW1-3) were installed under differing canopy densities to better understand groundwater recharge from snowmelt as it relates to the recent tree thinning operations. Percent canopy cover was determined by the remote sensing software Ecognition (AppendixD). SNOW1 (SM-2015) was placed under a dense canopy; 85% canopy cover. SNOW2 (SM-2016) was located in a mostly open clearing; 20% canopy cover. SNOW3 (SM-2017) was located under an intermediate density; 45% canopy cover. The melt collectors were installed within 240 yards of each other at an elevation of 7,800 ft. Two of the instruments are positioned on a southeast facing slope, while the third is facing northeast. The variability of the aspect between the sites is not believed to lead to significant complications as the slope where the instruments are positioned is relatively shallow, 15 degrees (Anderson et al., 1958).

While two melt collectors were initially installed for the 2011-12 winter, and the third snow melt collector was installed for the 2013-14, it wasn't until the 2014-15 winter that all of the deployed instruments functioned correctly and produced usable data. Having the full suite of three complete snow melt records from the same winter allowed for direct comparison between canopy densities. The remote nature of the project, coupled with the unfortunate necessity of placing the instruments under trees prone to dropping pines needles in the collection cone, lead to frequent clogging, and erroneous data. To get a better idea of what was going on, cameras programed to take daily photos of the snow melt collectors were installed. These photo-time-series allowed us to visually determine if a snow melt collector had stopped functioning or simply hadn't received precipitation.

Winter precipitation record

To measure the winter precipitation that fell throughout the study area we added anti-freeze attachment cylinders to our existing array of tipping buckets. The attachment is a simple device that fits over the existing tipping bucket, consisting of a reservoir that is filled with an anti-freeze solution, and an overflow tube. When precipitation falls in the antifreeze, the level in the reservoir rises and overflows, draining into the tipping bucket. While this method has been shown to be effective in some settings, we had a difficult time getting them to work consistently. Several researchers have pointed out flaws with the method, including surface tension in the overflow tube leading to blockage, high wind slashing the antifreeze out of the reservoir, and evaporation of the antifreeze solution (Das and Prakash, 2011). Due to the patchy unreliable data collected by the winterized tipping buckets, precipitation data from NOAA weather station US1NMOT0027 was used instead. This weather station is located 8.4 km northwest of the snow melt collectors at 8,800ft elevation.

While using data collected 8 km away is not ideal, it isn't as big of a concern when dealing with snow fall data. During the summer in the southwest, monsoon precipitation occurs as brief isolated thunderstorms, resulting in localized precipitation that can vary greatly over a short distance. In the winter, however, frontal storms are the primary source of precipitation. These storms are generally broader, resulting in more uniformly distributed precipitation patterns as they are controlled by regional weather patterns.

To study snow-melt loss in greater detail we broke the 2014-15 snow record up into individual storms. This was made possible using the photos-time-series to determining when snow first appeared, and how long it remained. Next, we used the snow melt data to determine how much SWE was measured during that same period, and finally we matched the snow event with gross precipitation record from the weather station. In this way we were able study each storm and subsequent melting, calculating what percent of each storm was lost, and the duration that the snow remained on the ground.

Using this data we were able to calculate the snow ablation rate (inches/day). The snow ablation rate is represented by the initial SWE (inches) on the ground directly after the storm, divided by the number of days of the ablation period. The summed snow melt data for each individual storm was used as the initial SWE.

Some additional filtering of the snow data was required to calculate the snow ablation rate. The snow ablation rate calculation assumes that the initial SWE is the maximum snow present. If another precipitation event occurred before the original had entirely melted the two were discarded.

RESULTS

Rain Interception Analysis

For the period during which rain precipitation and throughfall data were collected, approximately 192 events were analyzed, after winter precipitation and erroneous TFC data were filtered. Rain storms ranged from 0.25 mm to 62 mm. The mean storm size was 2.54 mm of rain.

The point of saturation corresponds well with the density of the canopy as seen in Table G1; the least dense tree canopy becoming saturated first after only 1 mm of rain, while the densest canopy requiring nearly 3.5 mm to reach saturation. The evaporation to rain ratio (E/R) follows this same trend, with smaller values associated with less dense canopy and higher value in denser stands. The rain rate at each location obviously stays constant, while the evaporation rate increases with density as there is greater surface area from which rain can evaporate from. The measured direct throughfall coefficent follows an inverse correlation with canopy density; a smaller fraction of direct throughfall associated with denser canopy and a larger direct throughfall associated with less dense canopy. Storage capacity, however, did not follow a distinguishable trend as would have been expected.

Table G1 Estimated canopy parameters.

	TFC1 (SM-5108)	TFC2 (SM-5109)	TFC3 (SM-5110)	TFC4 (SM-5111)	TFC5 (SM-5112)
Percent Canopy Cover	40.7 %	53.7 %	57.0 %	76.0 %	89.0 %
Precipitation to reach saturation (Ps) (inches)	0.04	0.09	0.1	0.11	0.14
Evaporation to Rain Rate Ratio (E/R)	0.28	0.32	0.33	0.55	0.72
Direct Throughfall Coefficient (p)	0.33	0.25	0.19	0.24	0.11
Percent Intercepted, calculated (I)	38.4 %	48.1 %	53.5 %	70.0 %	82.3 %
Mean canopy storage capacity (S) (inches)	0.02	0.04	0.05	0.02	0.02

Each storm included in the throughfall analysis was ranked and plotted on probability of exceedance curve (Figure G6). By plotting the point of saturation determined at each TFC site on this graph we can determine what the likelihood of throughfall occurring at different canopy densities. This found that 71% of storms were large enough to saturate the canopy of the least dense canopy we tested, while only 41% of storms recorded were large enough to lead to throughfall under the denser canopy (Figure G6).

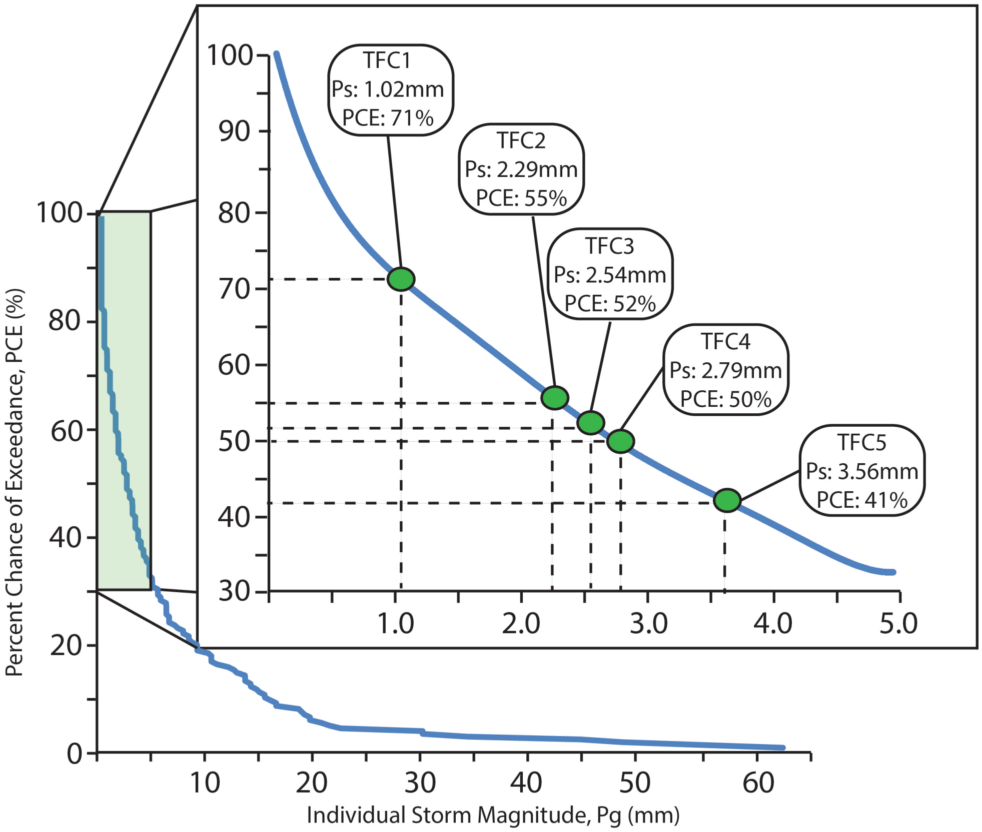

Figure G6: Exceedance curve analysis of storms, related to the saturation point measured under different canopy densities.

A strong relationship was found between the percent canopy density and the average interception calculated at each study site. By graphing percent interception against canopy density we were able to find a line of best fit that described the relationship between the two (Figure G7). Using the canopy density map created using Ecognition (Appendix D), we applied the relationship we found between interception and canopy density to the entire watershed to estimate interception throughout the entire watershed.

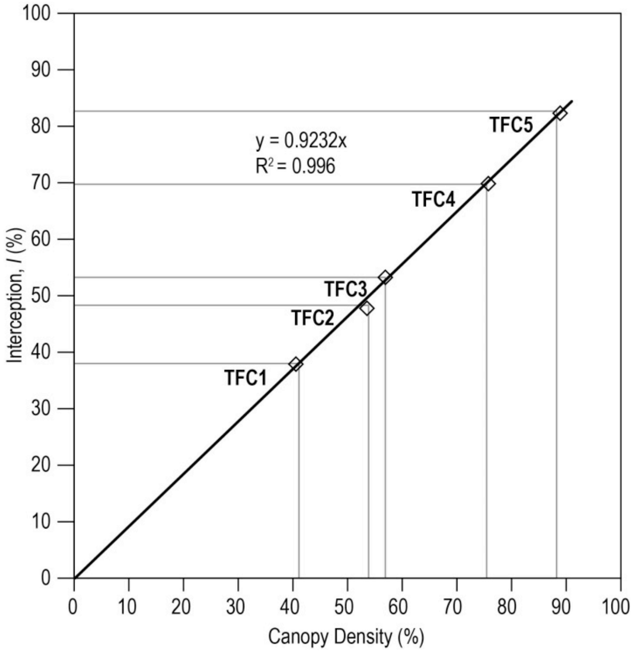

Figure G7: Canopy interception as a function of canopy cover. Linear regression shows a strong correlation.

Snow-melt Loss Analysis

Snow melt data from the melt collectors were plotted against the NOAA precipitation record (Figure G8). From this figure you can start to get a rough idea of how changes in canopy densities influenced the volume of snow each site recorded. Under the densest canopy (SNOW1) 79% of the total snow fall was lost over the course of the winter. 39% of the SWE that fell on the open canopy site (SNOW2) was lost, and 47% was lost under the intermediate canopy (SNOW3).

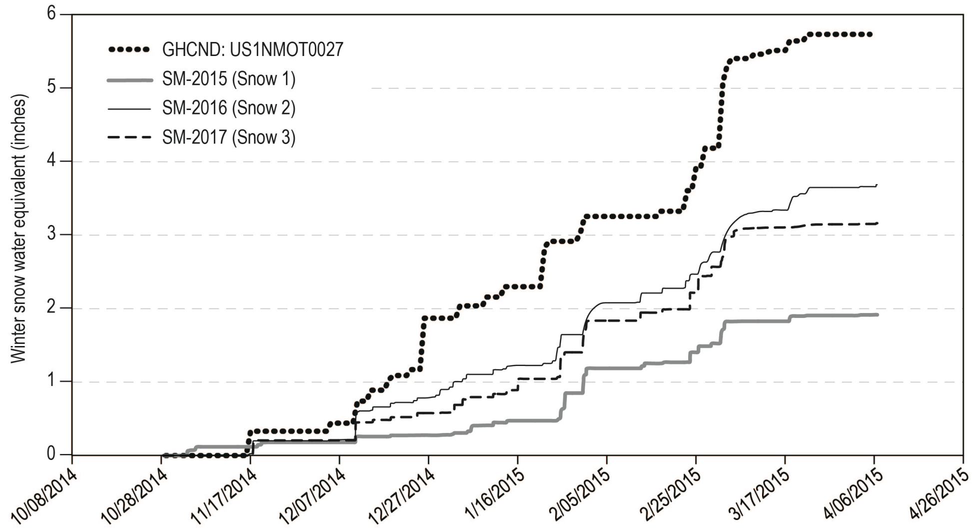

Figure G8: Cumulative snowmelt and SWE for the 2014-2015 winter season.

Comparing the interception of rain vs snow loss with regards to their respective canopy density we can make observations how the two processes relate. First, the snow loss percent under the dense canopy (85% canopy cover) plots very close to the rain interception rate under a similarly dense canopy. The intermediate canopy (45% canopy cover) lost more SWE than is modeled to be intercepted in the form of rain; 11% more snow loss. Finally, the site that was positioned under a relatively open canopy (20% canopy cover) had significantly more snow loss than would have been intercepted as rain; 53% more snow loss. There are several likely explanations for this discrepancy. First, sublimation, or snow evaporating directly into the atmosphere, is greater where there is direct sunlight striking the snow. Sublimation is also greater in the presence of wind. In open areas wind speed is typically greater than in thickly wooded areas. Additionally, wind typically blows snow from where it is thickest, to areas where it is thin, spreading the snow out evenly.

Table G2: Canopy cover and water loss data for snow collectors installed under different canopy densities.

	Snow 1 (SM-2015)	Snow 2 (SM-2016)	Snow 3 (SM-2017)
Percent Canopy Cover	85%	20%	45%
Percent Intercepted	79%	39%	47%
Ablation Rate (in/day)	0.031	0.103	0.069

Snow ablation rates follow a similar trend; under the densest canopy the average ablation rate was slowest 0.031 in/day. The open canopy was the quickest at 0.103 in/day, and the intermediate canopy recorded 0.069 in/day. This is easily demonstrated by figure G9. This figure shows the effect that canopy density had on the ablation rate. Not only is more meltwater recorded in the clearing (SNOW2) but snow also melts more quickly. Next, each snowfall’s ablation rate was plotted against the percent lost. This dataset demonstrates the higher the ablation rate, or the faster the snow is melted, the lower the percent loss.

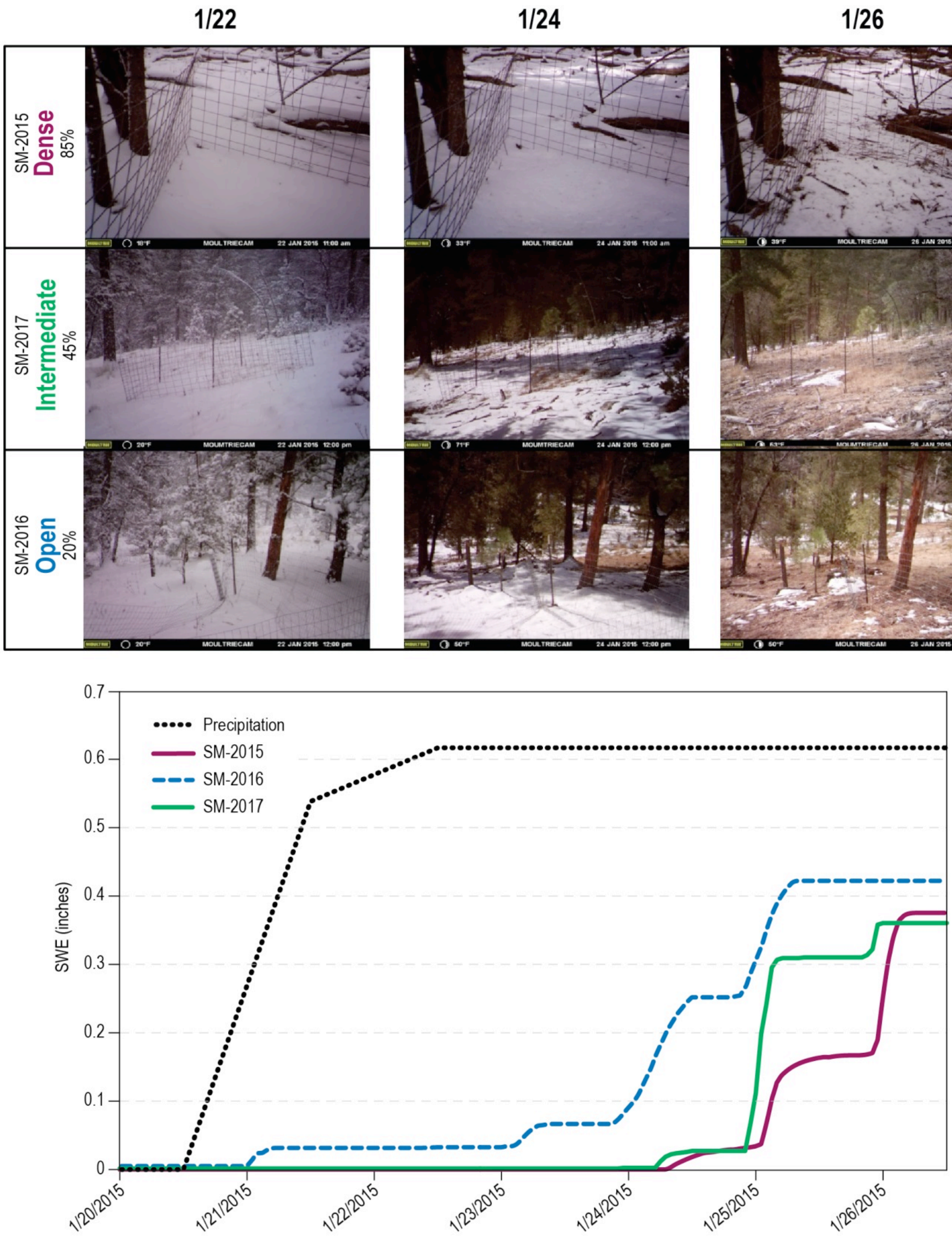

Figure G9: Cumulative snow melt and total SWE data for a snow storm in January 2015.

Conclusions

Tree thinning proved to have an impact on the frequency and volume of precipitation that has the potential to enter the ground. When precipitation falls as rain, a decrease in canopy density has a nearly proportionally decrease in interception. For example, we found that under a canopy density with nearly 89% cover only 82% of the gross precipitation was intercepted and lost from the system. When the canopy is roughly half as dense (41%), only 38% of gross precipitation was intercepted. With sparser foliage there is less surface area in the canopy with which to intercept rain. While this is a rather intuitive conclusion, the precise relationship that was determined for this localized study site improves our modeling of the effects of tree thinning.

The impact tree thinning had on winter precipitation, or snow, followed a similar trend. The relationship between interception and canopy cover is similar to rain when looking at the effect of thinning a dense canopy (85%) to a medium-dense (45%) cover. However, the impact of thinning a forest from medium-dense (45%) to sparse (20%) canopy cover was greatly diminished; leading to only an 8% decrease in snow-melt loss. The diminishing returns are largely the consequence of increased sublimation as result of higher wind speeds, and more direct sunlight.

Changing Climate: Winter Snow Pack

From 2005 to 2012 an investigation of the southern Sacramento Mountains was carried out by the New Mexico Bureau of Geology to characterize the hydrogeologic framework of the area (Newton et. al., 2012). One of the findings of the report was that the majority of recharge to the aquifers that extending far down slope to the east occurs in the high mountains, and primarily as winter precipitation. Despite the fact that far less of the annual precipitation for the area falls as snow, snowmelt exerts a stronger influence on groundwater recharge than does summer rainfall. Summer storm events in the Southwest are typically high intensity and short in duration (hours), which typically results in high overland flow, as opposed to infiltration. Snowmelt on the other hand results in low intensity, prolonged pulses of water (days), which is more likely to infiltrate instead of create runoff. Additionally, summer rains fall when temperatures are high and vegetation is at its most active, meaning evapotranspiration is significant. Snowmelt occurs when vegetation is mostly dormant and temperatures are low, minimizing evapotranspiration. Recharge takes place when enough water is present to exceed both the storage capacity of the soil and the potential evapotranspiration (Flint et al., 2004). They go on to state that the accumulation of snow over months-long period can often provide sufficient moisture to accomplish this during snowmelt.

The photo-time-series, however showed that over the past two years, snow in this watershed generally melts within a week of when it is deposited, leading to no winter long accumulation. It is hard to determine if this is a new trend. Studying a 100 year temperature record from Cloudcroft showed that daily average temperatures in the winter have remained steady. However, we found that daily highs have increased by as much as 1-2^0 C (~2-4^0 F) during the winter months over the past 100 years. To attempt to determine if snow had accumulated over the winter in the past we looked at Landsat satellite imagery. Landsat images are recorded every 16 days, covering the majority of the earth's surface, and have been collected for more than 30 years. These images consist of several spectral bands that have a variety of applications (landsatlook.usgs.gov). We were able to visually determine if there was snow on the ground, however, it was hard to determine if it was accumulated snow, or recent snowfall. From this it seems there were several winters in the 80's that saw winter accumulation and very few years since.

This raises more questions than it answers unfortunately. Do several rapid snowmelt events lead to more or less recharge than if the snowpack had built up all winter and melted all at once. From our work studying the ablation rate of snow in the area, we found that the quicker snow is melted, the less water is lost to sublimation. This would suggest that more water is potentially getting to the ground in years that snow does not build up. However, each snowmelt is typically small, and may not saturate the soil to the point that recharge can occur.

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