

Project Title: Effects of fuel treatments and wildfire on winter snowpack accumulation and depletion

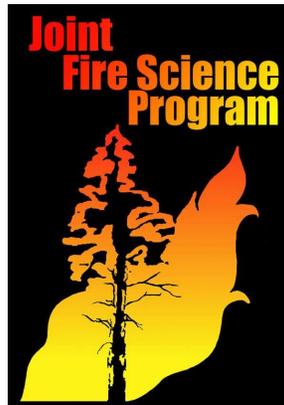
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Abstract:

Winter snowpack in dry montane regions provides a valuable ecosystem service by storing water into the growing season. Wildfire in snow-dominated montane forests has the potential to indirectly affect snowpack accumulation and ablation (melt) rates by reducing canopy cover, which reduces snow interception and albedo but also increases solar radiation and wind speed. These counteracting effects of canopy removal mean that the net effect of wildfire impacts on snowpack depth and duration is uncertain, and likely scale-dependent. In this study I tested whether low to intermediate levels of wildfire severity maximize snowpack depth by increasing accumulation while slowing melt, using gridded, repeated snow depth measurements from 3 fires in the Sierra Nevada of California. Ablation effects of canopy disturbance dominated snow depth patterns: increasing fire severity had a strong negative effect on snowpack depth. Contrary to expectations, the unburned forest condition had the highest overall snowpack depth, and mean snow depth among all site-visits was reduced by 78% from unburned forest to high-severity fire. However, at the individual tree scale, measurements underneath canopy had significantly less snow than measurements in gaps, controlling for effects of fire severity and aspect. This apparent paradox in snowpack response to fire at the individual tree vs. landscape scales is due to greater variation in canopy cover in unburned and very low severity areas, because many trees survive low-severity fire to create small areas for snow accumulation while reducing ablation. Efforts to maximize snowpack duration in montane forests should focus on retaining fine-scale heterogeneity in forest structure.

II. Background and Purpose

Snowpack and fire are two critical ecosystem processes in montane conifer forests of western North America (Marshall et al. 2008). Snowpack depth is a major driver of forest productivity, particularly in Mediterranean climate forests of California, where a majority of precipitation falls in the winter (Trujillo et al. 2012). Snowpack also facilitates decomposition of organic material and mineralization of nutrients underneath the snow, which increases uptake efficiency and nutrient availability for plant growth as temperatures warm in the spring (Johnson et al. 2009). By holding moisture aboveground through the spring and slowly releasing it into the soil, longer snowpack duration can lead to increased soil water availability longer into the growing season (Marshall et al. 2008). A persistent winter snowpack provides important ecosystem services for downstream users, with cooler temperatures and deeper snowpack delaying peak runoff flows in rivers later into the summer (Hunsaker et al. 2012), when demand for agricultural and urban use increases (Schlenker et al. 2007). Earlier snowmelt runoff, conversely, can lead to reservoir capacity being exceeded, and reduce hydropower generation during the summer (Bales et al. 2011b). There is strong consensus among climate change studies that warmer temperatures will lead to decreased snowpack volume and earlier snowmelt, particularly at lower elevations (Stewart et al. 2004, Howat and Tulaczyk 2005, Mote et al. 2005, Stewart 2009, Kapnick and Hall 2010).

Fire is an important driver of forest structure and associated ecosystem processes in montane mixed-conifer forests (Sugihara et al. 2006, Safford and Stevens *In Press*). In more frequent-fire forests, fire maintains a heterogeneous landscape pattern dominated by generally small (< 1 ha) gaps, small clumps of trees and more widely spaced large fire-resistant trees, with low fuel loads (Larson and Churchill 2012, Lydersen et al. 2013). This heterogeneous structure creates forests that are resilient to drought, disease and recurring fires, while promoting increased rates of nutrient cycling and increased plant diversity (Safford and Stevens *In Press*). In less frequent fire forests, often at higher elevation, fire can create large patches of complete tree mortality followed by rapid forest regeneration (if trees have specific post-fire regeneration mechanisms) or extended periods of shrub or grass dominance. The frequency and intensity of fires across the western US is generally expected to increase in the future, due to both climate change and past management practices that have altered forest fuel structure (Westerling et al. 2006, Safford and Stevens *In Press*).

Despite the profound importance of these two ecosystem processes, their interaction is rarely studied. However, snowpack and fire have important reciprocal interactions. Snowpack can influence fire probability, with lower snowpack years contributing to longer fire seasons (Westerling et al. 2006) and possibly greater probability of lightning strikes (Lutz et al. 2009). Fire, conversely, can significantly modify forest canopy structure and albedo, which can in turn modify accumulation and ablation (depletion) of snowpack (Storck et al. 2002, Varhola et al. 2010, Molotch et al. 2011, Lydersen and North 2012).

The effects of forest structure on snowpack are complex (Coughlan and Running 1997, Molotch et al. 2011). Tree canopies intercept falling snow, which can then either sublimate back to the atmosphere (particularly in drier climates), drip to the ground as liquid water, or fall as solid mass (Storck et al. 2002). The net effect of these processes is that initial post-storm snowpack accumulation totals are reduced as canopy cover increases, on the order of approximately 4% reductions in snow accumulation per 10% increases in canopy cover (Varhola et al. 2010), and vice-versa. However, percent canopy cover can be defined at many spatial scales, from the small plot-scale to the landscape-scale, and as the spatial scale of canopy cover definition increases, the ability to identify the effects of heterogeneous canopy patterns on snowpack accumulation diminishes (Varhola et al. 2010).

While forest canopy cover reduces initial snow accumulation, it also slows ablation rates, by reducing direct shortwave (solar) radiation on the snow surface, reducing temperatures in the forest understory, and reducing wind speeds (Kershaw 2001, Burles and Boon 2011, Molotch et al. 2011). Reductions in ablation rates tend to occur on the order of 6% per 10% increases in canopy cover (Varhola et al. 2010). The amount of direct beam solar irradiance is the strongest predictor of ablation rates on sunny days, while the amount of diffuse irradiance (represented by hemispherical measurements of canopy openness) is a better predictor of ablation rates on cloudy days (Musselman et al. 2012); thus the landscape position, aspect, and size of canopy gaps is likely to influence ablation rates via a series of biophysical interactions that ultimately determine the amount of energy reaching the snowpack surface.

Because canopy disturbance has counteracting effects on snowpack, by increasing accumulation but also increasing ablation, there remains substantial uncertainty over which of these processes ultimately predominates in determining snowpack duration (Bales et al. 2011b). In part, the uncertainty is because the answer to this question depends on a wide range of co-varying factors, including but not limited to elevation, temperature and precipitation, slope and aspect, cloudiness (which all influence initial snowfall amounts, sublimation, and melt rates independent of canopy architecture), canopy leaf area index (LAI), gap size, and disturbance type (Coughlan and Running 1997, Kershaw 2001, Musselman et al. 2008, Dobrowski 2010, Varhola et al. 2010, Molotch et al. 2011, Bales et al. 2011a). This uncertainty is manifest in contradicting results; for instance Burles and Boon (2011) and Micheletty et al. (2014) find decreased snowpack duration in canopy gaps relative to closed canopy forest, while Bales et al. (2011a), Molotch et al. (2009), and Coughlan and Running (1997) document instances of increased snowpack duration in canopy gaps relative to closed canopy forest. Furthermore, despite the importance of fire regimes in driving canopy architecture at multiple scales, studies that have previously examined fire effects on snowpack dynamics are often based on single plots or single burn events, or use streamflow as a proxy for snowpack dynamics across entire watersheds (e.g., Seibert et al. 2010, Burles and Boon 2011, Pomeroy et al. 2012), without

capturing important scale-dependent effects of forest canopies, or determining consistency of effects across multiple fires.

For this research, we used fine-scale snow survey data from three recent wildfires to investigate the effects of fire severity on snowpack depth at multiple scales. These surveys captured a range of fire severities, and quantified snow depth and water content across multiple site visits, to test the following hypotheses: 1) mean snow depth should be greatest in burned areas of low-severity fire, where increases in canopy gaps relative to unburned forest maximize snow accumulation while retention of moderate forest canopy cover slows melt rates relative to more severely burned forest; 2) mean snow depth should be greater when overhead canopy cover is absent relative to underneath tree canopies, controlling for the effects of severity; 3) mean snow depth should be higher on northeast aspects than southwest aspects; 4) increasing size of high-severity patches should have a negative effect on snow depth, with the opposite size effect in low-severity patches; and 5) variance in snow depth should be maximized by low-severity fire.

III. Study description and location:

Original design:

This project was originally intended to use these same methods to measure snowpack effects in response to the factorial combination of fuel treatments and wildfire, using an existing network of sites where wildfire had burned into fuels treatments (Stevens et al. 2014). Following the original proposal protocol, we deployed a network of iButton sensors and cameras in advance of the winter field season to the 5 existing sites (Angora, American River, Cascadel, Harding and Silver) that were most likely to receive snow in the winter and also be accessible to field crews.

However, winter 2014 was one of the warmest and driest winters on record in California. As a result of this historic drought, only the highest-elevation of these sites (the Angora fire in South Lake Tahoe; elevation 1950 m) received more than one snowstorm depositing > 20 cm of snow. Of the few other precipitation events, the iButton data revealed that most of that precipitation fell as rain, and the snow that did fall rarely persisted for more than three days. The number of snow events that persisted for greater than 3 days on average among all iButton sample points within a transect were: 2 for American River, 8 for Angora, 4 for Cascadel, 2 for Harding, and 3 for Silver. As a result, we deployed the research crew to two additional high-elevation fires to which we could gain access, where snow cover was greater and we could establish a grid of points to be re-sampled (see description below). The consequence of this was that we were not able to fully tease out treatment effects in unburned forests; however we still captured the full gradient of fire severity (see below).

Implemented design

Field crews sampled snow depth at three different wildfires in the Sierra Nevada of California during winter 2014 (Figure 1). The Angora Fire on the Lake Tahoe Basin burned in 2007 at predominantly high-severity, although fuel treatments reduced fire severity in some areas (Safford et al. 2009). Crews sampled linear grid points overlaid on top of four existing transects used to measure fuel treatment effects on fire behavior (Stevens et al. 2014), which spanned the boundary between high- and low-severity within the fire, and treated-untreated areas outside the fire, for a total of 129 sample points. The sampled area was 26 ha, and the four transects were distributed across approximately 400 ha. The Showers Fire in the Lake Tahoe Basin burned in 2002 at predominantly moderate-to high- severity, the sampled area included 156 sample points arranged in a 30m grid covering 21 ha. The Reading Fire burned in Lassen National Park (where the sampling occurred) and Lassen National Forest, burning over 11,000 ha at a mix of severities. The sampled area included 520 sample points arranged in a 60 m grid covering 187 ha, although only 285 of the 520 points were sampled on the first visit. Each sampling effort spanned 2-3 days; the Angora Fire was sampled six separate times, the Showers Fire was sampled three times and the Reading Fire was sampled two times for a total of 11 unique site-visits. These gridded

sampling designs allow for landscape scale models to predict snow depth and water content based on topographic and forest structural features (Rice and Bales 2010).

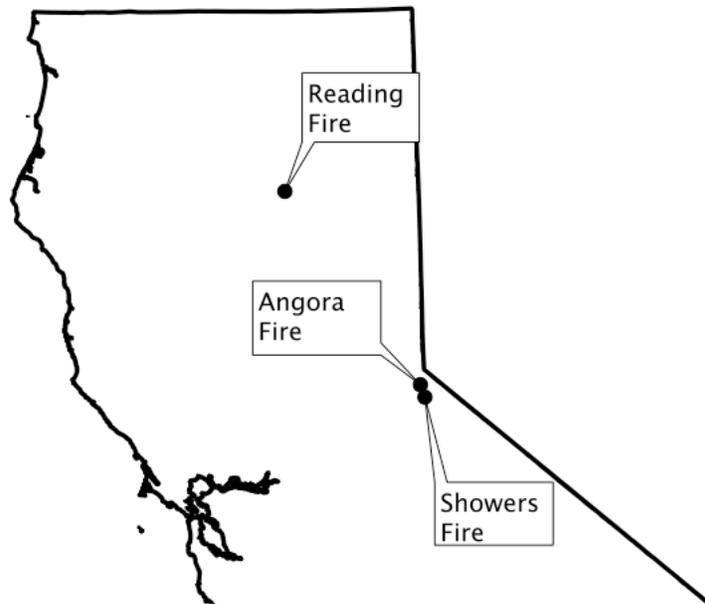


Figure 1: Map of study locations, in northern California

Each site visit was conducted between 2 and 14 days of the most recent snowstorm to deposit at least 10 cm of snow, with the exact visit date determined by road conditions and other accessibility issues. At each site visit, crews measured depth of snowpack at pre-determined grid points, measuring from the snow surface to the soil surface, using graduated avalanche probes. At each point, the overhead canopy condition was assessed as either being open, at the drip edge of live tree canopy, or underneath live tree canopy (variables were classified as “open”, “edge” and “under”). At a subset of points for each site visit where the canopy condition was open, crews measured soil water content in cm^3 , calculated as the mass of snow per 1000 cm^3 of snow volume.

The fire severity at a given sample point was extracted from the Monitoring Trends in Burn Severity (MTBS; www.mtbs.gov) layers for each fire. Severity within the fire perimeter is classified into four severity classes depending on the extent of pre- to post-fire vegetation change within a given pixel, at a 30-m (0.09 ha) pixel resolution. In order of increasing fire severity, class 1 ranges from 0-5% change (“very low”), class 2 from 5-25% change (“low”), class 3 from 25-75% change (“medium”), and class 4 >75% change (“high”) (www.mtbs.gov), while a fifth class (“class 0”) consisted of sampling points outside the fire perimeter. For the Reading Fire, which had sample points evenly distributed among the 4 severity classes, I calculated the patch size for each of the four severity classes in order to examine patch size effects on snow depth.

Patches that were less than 30 m wide in the center but expanded on either side were broken into separate patches; this was most common in moderate-severity “rings” that surrounded high-severity patches. There were 11 very low severity patches (mean size 10.3 ha), 17 low severity patches (mean size 4.7 ha), 14 medium severity patches (mean size 7 ha) and 7 high severity patches (mean size 11.6 ha) across the study area. Importantly, low severity patches were always adjacent to very low and/or moderate patches; moderate severity patches were always adjacent to low and/or high severity patches, and so on. Aspect was classified at each sample point using a 30-m resolution DEM-derived raster layer, and categorized as “flat” (if slope was < 2 degrees from horizontal), “northeast”, or “southwest (with breakpoints between the two slope classes at 135 and 315 degrees azimuth).

Analysis

To test the hypotheses that snow depth responds differently to post-fire canopy cover at different spatial scales, we constructed a set of linear mixed models that predicted snow depth as a function of three predictors: burn severity (hypothesis 1), overhead canopy condition (hypothesis 2), and aspect (hypothesis 3), and all possible combinations thereof. Each model included a random intercept for sampling week nested within site, to account for the non-independence of point measurements across space and time. The model therefore adjusted the overall intercept according to the mean snow depth at a given site on a given sampling week. Residual variance in snow depth after accounting for week and site effects was explained using fixed effects terms for severity, overhead canopy and aspect, both separately and in combination (Table A1). The contribution of each predictor variable, separately and combined, to improving the overall model fit was assessed by comparing the Bayesian Information Criterion (BIC) among the full suite of models. Models were fit using the lme4 package in R (Bates et al. 2013). Additionally, pairwise comparisons among different factor levels for each of the three fixed effects terms were tested for statistical significance using a t-distribution and estimating the degrees of freedom from the mixed-effects model using the Kenward-Rodgers approximation in the R package pbkrtest. Because the degrees of freedom in mixed-effects models are difficult to estimate, these p-values are interpreted cautiously along with evidence from model comparisons and parameter estimates to draw conclusions from the data.

To test the hypothesis that patch size should influence snow depth, WE built a linear mixed-effects regression model for the Reading Fire data, with snow depth contingent on burn severity class at a given point, as well as patch area of that burn severity class and an interaction between the two variables. To test for different patch size effects depending on burn severity class, WE calculated t-statistics and associated p-values for the interaction coefficient between patch size and each burn severity class, again using the Kenward-Rodgers approximation. we also tested the hypothesis that variation in snowpack within a given burn severity class should be highest at low-severity fire, by calculating the variance in snow depth within each severity class for each week, and regressing those values against severity class (coded as a numeric value 1:4).

We estimated total water storage across burn severity classes at the Reading Fire on April 16, using the mean snow water equivalent (SWE) value from that sample visit (n=7 samples; mean= 439 cm³ water/ 1000 cm³ snow; standard deviation=34.9). At each point, we calculated the SWE depth of the snowpack in cm water, by multiplying the snowpack depth by 0.439. To compare the contributions of each of the 13 unique burn severity-overhead canopy combinations to total site SWE, we first calculated the fraction of the landscape covered by each of the 13 combination classes, defined as the number of sample points falling in that class divided by the total number of sample points (520). Because sample points were laid out on a 60-m grid, we calculated the area in hectares represented by each combination class as the number of sample points in that class multiplied by 0.36 ha. Finally, we calculated total water volume in snowpack by multiplying the area sampled in each combination class by the SWE depth of that class.

IV. Key Findings:

Parameter estimates from the full best-fit model indicate that increasing fire severity was associated with significantly decreased snow depth (Table 1), controlling for the effects of fire severity and aspect as well as variation in overall snow depth among site visits. Mean snow depth in the unburned class was 25.8 cm across all site-visits, overhead canopy conditions and aspects (Fig. 2a). Each successive increase in fire severity class caused an additional reduction in average snow depth, all other conditions being equal (19.7 cm in class 1, 13.2 cm in class 2, 11.4 cm in class 3, 5.7 cm in class 4; Fig. 2a). However, at the point-scale, the effect was reversed (Table 1). There was a significant decrease in snow depth moving from underneath live tree cover to the canopy edge and again to a canopy gap (Table 1), even while accounting for effects of fire severity, aspect, and site visit. The average snow depth underneath a live tree canopy was 10.7 cm (Fig. 2b), which increased to 15.2 cm at the canopy edge and 19.5 cm in canopy gaps. As expected, northeast aspects had significantly greater snow depth than flat slopes, and southwest aspects had significantly less snow depth than flat slopes, but the magnitude of these effects were generally less than the magnitude of canopy and fire effects (Table 1).

		Base condition:	Snow depth estimate (cm)	Standard Error		
		Closed canopy, no fire, flat:	23.73	11.34		
		Altered condition:	Parameter estimate	Standard Error	T statistic	P-value
Canopy	Canopy edge		4.81	1.05	4.59	0.04
	Canopy gap		8.2	0.84	9.76	0.01
Fire	Very low severity		-7.18	1.55	-4.63	0.04
	Low severity		-12.68	1.1	-11.51	0.01
	Moderate severity		-14.1	0.99	-14.3	0.003
	High severity		-19.22	1.08	-17.82	0.002
Aspect	Northeast aspect		6.63	0.96	6.9	0.02
	Southwest aspect		-3.41	0.92	-3.72	0.06

Table 1: Model output. Parameter estimates are from a full model without interactions between terms; parameter estimates indicate effect size relative to the base condition

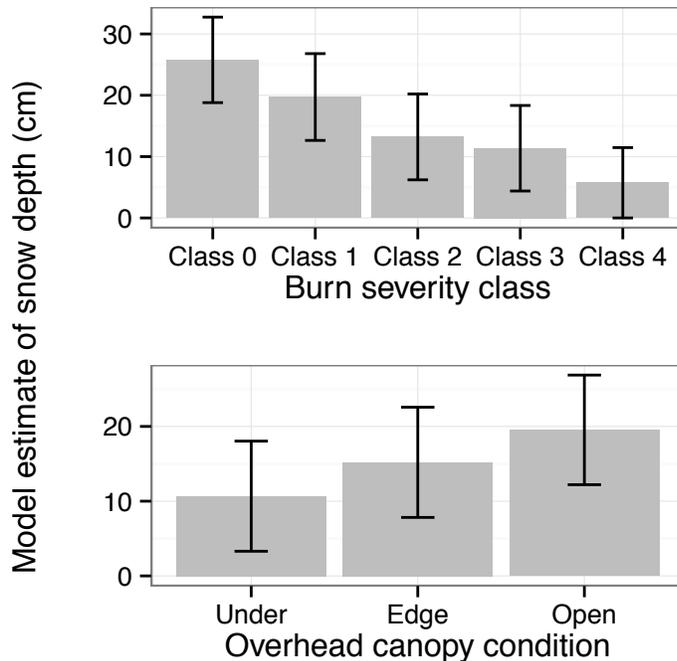


Figure 2: Model-estimated snow depth among different burn severity classes and overhead canopy gradients.

The effect of patch size on snow depth at the Reading Fire was dependent on which burn severity class a sample point fell into. A model including an interaction between patch size and burn severity had more support than either a model with burn severity alone (dBIC=3.9) or a model with burn severity and patch size but no interaction (dBIC=12.7). The interaction was primarily driven by the very low severity burn class, where the effect of patch size was positive, compared to a negative patch size effect for the other three burn severity classes (Fig. 3). The coefficients for the interaction terms between patch area and both high (-0.80) and moderate (-1.12) severity burn classes were significantly negative relative to the very low severity class ($t = -4.06, -5.86$; $P = 0.038, 0.016$ respectively), and the interaction between patch area and low-severity burn class was also negative (-0.86, $t = -2.55$, $P = 0.10$). Most incidences of points in the low, moderate and high severity classes having snow depths greater than 20 cm occurred in patches less than 5 ha (Fig 3). Mean patch size was 3.4 ha. Regardless of patch size, predicted snow depth tended to decrease with increasing severity (Fig. 3). Correspondingly, the variance in snow depth within a severity class decreased linearly with increasing severity (Fig. 4; $R^2 = 0.74$, $t = -4.78$, $P = 0.001$).

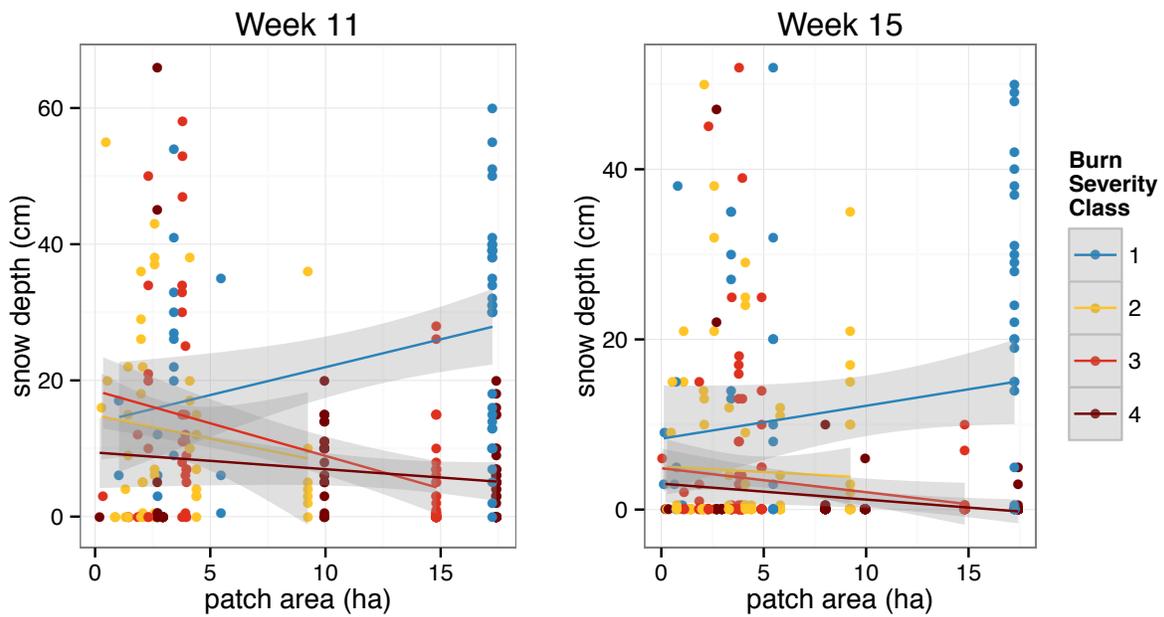


Figure 3: Patch area effects on snow depth, for two different weeks at the Reading Fire: (a) week 11, and (b) week 15.

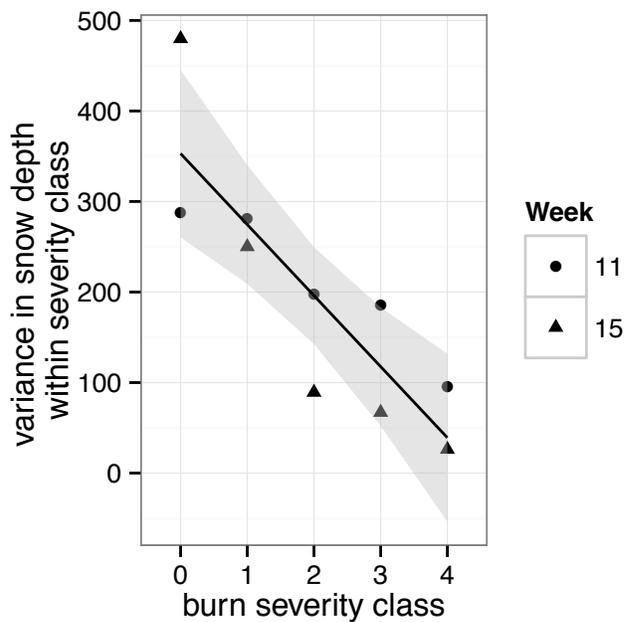


Figure 4: Variance in snow depth at the Reading Fire, at two different sampling weeks (11 and 15), within a single burn severity class.

Despite representing 19% of the total sampled area, the unburned severity class accounted for 57% of the total water volume in snowpack at the Reading Fire on April 16 (Fig. 5b). The unburned and very low severity classes together combined for 78% of total water volume (Fig. 5b). Within the theoretically “closed canopy” forest of the unburned condition, the proportion of sample points in the open (not underneath or at the edge of live tree canopy) was substantial at 43%; conversely, 100% of sample points in the high-severity class were in the open (Fig. 5a). Canopy cover estimates from unburned to high severity using this approach are 57%, 42%, 25%, 9% and 0%, for classes 1-5 respectively.

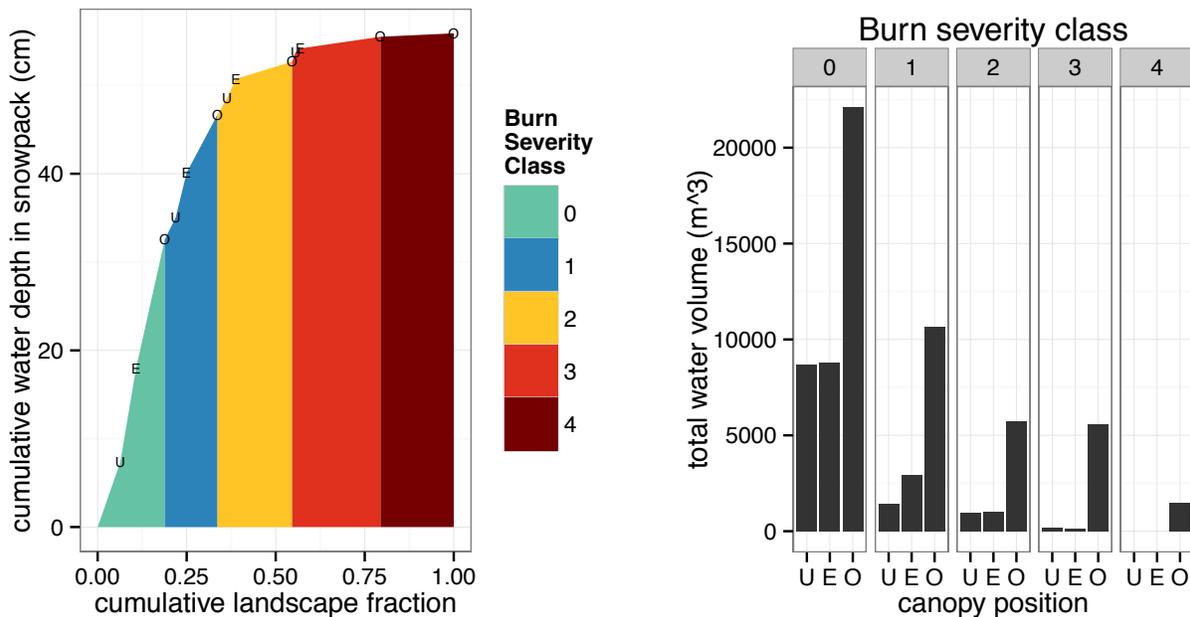


Figure 5: Cumulative depth (a) and volume (b) of water contained in snowpack at the Reading Fire on April 15, by burn severity class (0= unburned, 4= high severity) and overhead canopy position (U= under, E= edge, O= open). Cumulative water depth in (a) represents the total depth of snow among all points within a given severity class-overhead canopy combination, multiplied by the total snow water equivalent fraction for the Reading week 15 site visit (0.44). Bar colors represent severity class and letters represent overhead canopy position within that severity class. The height of a given severity-canopy indicator letter indicates the cumulative water depth for that set of sample points, and the position along the x axis indicates the cumulative landscape fraction represented by that set of points. The product of the water depth and the area covered by that set of points then gives the total water volume, shown in (b). There were no “edge” or “under” conditions represented in the high severity burn area (class 4).

We did analyze the iButton sensor data from the 5 original fires (including Angora). We used mixed-effects models similar to those used in the analyses described above, with the main predictor of snow-covered days and final snow day being a 4-factor variable for the factorial combination of burning and thinning. Although the sample sizes were too small to detect significant effects of burning and thinning (2 sensors per combination of burning/thinning, which were originally intended to corroborate field measurements), the trends follow those found at our more intensively sampled fires. The total number of snow-covered days (indicated by noon iButton temperature readings between -1°C and 1°C) was highest in the unburned-treated forest type, and lowest in the burned-untreated (high-severity) forest type. There was a significant difference between those two forest types, but no others. The results were qualitatively the same when we analyzed the last date of snow cover, however there were no significant differences among groups.

Main conclusions

Consistent patterns of scale-dependent post-fire snowpack dynamics emerged from the 11 site-visits in this study. At the stand- to landscape-scale (>0.09 ha grid resolution), increased canopy cover – represented by lower burn severity – was associated with increased snowpack depth at a given point in time. However, at the scale of individual sampling points, overhead canopy cover was associated with decreased snowpack depth (Fig. 2). These results suggest that as the spatial scale of canopy gaps increases, the predominant control over snowpack duration switches from canopy effects on accumulation, to canopy effects on ablation rates. In other words, when canopy disturbances are larger in scale, the associated increases in snowmelt outweigh the increases in snow deposition into these gaps, and snowmelt occurs faster. This conclusion is supported by the stronger effect sizes of fire severity relative to overhead canopy cover (Table 1), the negative effect increased of moderate- and high-severity patch sizes on snow depth (Fig. 4), and the reduced effect of overhead canopy on snow water equivalent at increasing levels of fire severity (Fig. 5a).

The finding that low severity fire was associated with lower overall snow depth than unburned forest ran counter to original hypothesis 1 (Fig. 2a; Fig. 5), although the decrease in snow depth at increasingly high severities was expected. Data suggest that the unburned forest in these sites may have fairly low and discontinuous canopy cover, thereby allowing substantial accumulation in gaps within the unburned condition. The proportion of sample points with open overhead canopy in the unburned condition ranged from 35% at Angora to 43% at Reading and 57% at Showers; these open points in unburned forests contributed substantially to the total snowpack water storage (e.g. Fig. 5b). Furthermore, the difference in snow depth between very low severity and unburned at the Reading Fire was substantial: a 15% decrease in canopy cover led to a 57% reduction in snow depth. This suggests two possible explanations: there may be a critical threshold of canopy cover (perhaps between the 57% found in the unburned condition and the 42% found in the very low severity class) below which solar radiation exerts a much

stronger effect on snow ablation. Alternatively, and perhaps more likely, the charred trunks, woody debris, and often abundant needle-cast following fire likely decrease the snow-surface albedo, increasing shortwave absorption and longwave transmittance of energy to the snowpack, which in turn speeds ablation (Winkler et al. 2010, Pugh and Small 2012, Gleason et al. 2013). Substantial bark char and crown scorch are associated with even low-severity post-fire conditions (Stevens et al. 2014).

V. Management Implications:

Provision of water, in the form of snowpack, is often invoked as a valuable ecosystem service provided by montane forests (Bales et al. 2011b). Land management agencies may therefore have incentives or mandates to manage these forests in order to maximize the value provided by this service, i.e. create conditions that promote long snowpack duration (Bales et al. 2011b). This is especially critical given the expected decrease in total snowfall under climate change, the increased sensitivity of snowpack to forest structure under low-snowpack conditions, and the ongoing increases in wildfire activity (Westerling et al. 2006, Kapnick and Hall 2010, Bales et al. 2011b). These results suggest that snowpack duration is longest when the extent of canopy loss due to fire is minimized. In fact, unburned conditions generated the most persistent snowpack, although this was facilitated by 37-53% canopy openness among the three fires studied. Because of the negative effect of direct canopy closure on snowpack accumulation, a completely closed-canopy forest would be likely to exhibit reduced snowpack duration, and certainly reduced snowpack volume, relative to a partially open forest. Closed-canopy forests are also at greater risk of burning at high-severity when they do eventually burn (Safford et al. 2012), which would create conditions favorable to shorter snowpack duration, at least in the areas in this study.

Because the forest stands with the greatest overall snowpack depth also had the highest variance in snowpack depth (e.g. the unburned and very low severity conditions, Fig. 4), heterogeneity in canopy cover is likely to be important for maximizing landscape-scale snowpack duration. There is strong evidence that such landscape-scale heterogeneity was a common historical condition in mixed-conifer forests of the Sierra Nevada and other regions in the Western US, and that this heterogeneity provided a range of other valuable services, including habitat diversity for wildlife and resilience to large-scale high-severity fire (Lydersen and North 2012, Lydersen et al. 2013, Kane et al. 2014, Safford and Stevens *In Press*). The data presented here suggest that snowpack provisioning may be another benefit to increasing and maintaining forest heterogeneity in forests that currently have homogenously high canopy cover, though a combination of fuel reduction treatments, prescribed fire, and managed wildfire. However, some untreated forests may currently be configured to maximize snowpack duration.

VI. Relationship to Other Recent Findings and Ongoing Work on This Topic:

The finding that ablation processes are more influential to total snowpack duration than accumulation processes in post-fire landscapes has several possible explanations. Water-year 2014 in California was one of the driest on record, with total snowfall totals in the Sierra Nevada X% of average, and the lowest on record (http://www.wcc.nrcs.usda.gov/nwcc/rgrpt?report=swe_hist&state=CA). Studies that have sampled canopy effects on snowpack over multiple years have found that ablation rates in low-snowpack years tend to be greater than in high-snowpack years (Woods et al. 2006, Molotch et al. 2009), likely due to a combination of warmer temperatures, greater evaporative demand and increased sunlight generally associated with drought conditions, and increased exposure of surface structures such as tree trunks and rocks that reduce surface albedo and emit longwave radiation and sensible heat. Furthermore, gaps and canopy openings in burned forests likely have different dynamics than in unburned forests, which might increase the influence of ablation over accumulation in determining snowpack duration. Most of the studies to document shorter snowpack duration in openings than under forest canopy come from burned forests (Seibert et al. 2010, Burles and Boon 2011, Gleason et al. 2013, Harpold et al. 2014), while most studies that document greater snowpack duration in openings than under forest canopy come from unburned forests (Coughlan and Running 1997, Molotch et al. 2009, Bales et al. 2011a, Bales et al. 2011b). This further suggests that longwave radiation increases and surface albedo decreases in burned forests due to charred wood, woody debris and litter fall, as described above.

Increasing fire severity was associated with lower snowpack depth despite all site visits being conducted within 14 days of the most recent large storm. Therefore, any initial increase in snow depth in high-severity areas at these three fires – via increased accumulation from lack of canopy – quickly dissipated due to rapid ablation. Other studies have suggested that large post-fire openings may lead to increases in soil water content, even if snowmelt rates may increase, because total snow volume is higher and soils may thaw earlier (Ebel et al. 2012). However, the duration of soil water storage will largely depend on soil porosity and water holding capacity; in well-drained soils like those in the Sierra Nevada, water from early snowmelt may rapidly be exported to the groundwater table and eventually lost from the system via stream discharge (Bales et al. 2011b). Such losses may heighten the asynchronicity between water availability and water demand (by both vegetation, such as regenerating or planted trees, and downstream human users during the spring and summer growing seasons).

VII. Future Work Needed:

Increased measurement resolution of canopy spatial patterns at multiple scales, combined with fine-scale prediction of snowpack depth across time and space using remote sensing tools such as LiDAR, are promising avenues for further research on the complex interactions between forests, fire, and snow. While this study identified the importance of spatial scale of canopy openings for post-fire snowpack dynamics, there is much more to be gained from a method such as LiDAR that could take repeated measurements over time, which would disentangle accumulation effects from ablation effects. Furthermore, a LiDAR approach could identify how important multiple canopy strata are to interception, and use fine-scale spatial data on gap size and shape to identify the optimum gap size and pattern across the landscape.

To pursue these questions, I am partnering with Jim Roche, a PhD student at UC Merced, to analyze a recent series of winter LiDAR flights from the Illillouette basin. The Illillouette is a well-studied, frequent-fire watershed in Yosemite National Park, which has been the subject of extensive research on the effect of multiple fires on subsequent fire severity and tree spatial patterns (Collins et al. 2007, van Wagendonk et al. 2012). We will use novel methods of characterizing forest gaps (Lydersen et al. 2013, Moeser et al. 2015) to improve our capacity to predict snowpack responses to fire and forest disturbance using airborne remote sensing technology.

VIII. Deliverables Crosswalk:

Proposed	Delivered	Status
Submission of manuscript to peer-review journal	Stevens, J.T. in prep. Scale-dependent effects of post-fire canopy cover on snowpack depth in montane coniferous forests.	In prep. For submission to <i>Ecosystems</i> . Expected submission 8/31/15
Fire Science Consortium webinar	N/A	Webinar has not yet been scheduled, pending submission and acceptance of manuscript. A talk has been accepted at the 2015 annual meeting of the Ecological Society of America to present these results: http://eco.confex.com/eco/2015/meetingapp.cgi/Paper/54702

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X. Additional Reporting (Appendices and other inputs to JFSP)

Appendix Table A1: Model selection results

Model variables	dBIC	df
BurnSev + Cpos + Aspect + (1 Week/Site)	0	12
BurnSev + (1 Cpos) + (1 Aspect) + (1 Week/Site)	17.82160134	10
CPos + (1 BurnSev) + (1 Aspect) + (1 Week/Site)	19.22505744	8
CPos * BurnSev + Aspect + (1 Week/Site)	20.35169964	20
BurnSev + (1 CPos) + (1 Week/Site)	132.1624101	9
CPos + (1 BurnSev) + (1 Week/Site)	133.3447883	7
BurnSev + (1 Week/Site)	202.599295	8
Aspect + (1 Week/Site)	312.3178581	6
(1 Week/Site)	400.8520176	4
CPos + (1 Week/Site)	406.5307821	6