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Scale-dependent effects of post-fire canopy cover on snowpack depth in montane coniferous forests

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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 coniferous montane forests has the potential to indirectly affect snowpack accumulation and ablation (mass loss) rates by reducing canopy cover, which reduces canopy interception of snow but also increases solar radiation and wind speed. These counteracting effects create uncertainty regarding the canopy conditions that maximize post-fire snowpack duration, which is of concern as montane regions across the western United States experience increasingly warm, dry winters with below-average snowpack. The net effect of wildfire on snowpack depth and duration across the landscape is uncertain, and likely scale dependent. In this study, I tested whether intermediate levels of wildfire severity maximize snowpack depth by increasing accumulation while slowing ablation, using gridded, repeated snow depth measurements from three fires in the Sierra Nevada of California. Increasing fire severity had a strong negative effect on snowpack depth, suggesting that increased ablation after fire, rather than increased accumulation, was the dominant control over snowpack duration. 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, snowpack depth was greater under canopy openings than underneath canopy, controlling for effects of fire severity and aspect. This apparent paradox in snowpack response to fire at the stand vs. individual tree scales is likely due to greater variation in canopy cover within unburned and very low severity areas, which creates smaller areas for snow accumulation while reducing ablation via shading. Management efforts to maximize snowpack duration in montane forests should focus on retaining fine-scale heterogeneity in forest structure.

Key words: fire; forest structure; heterogeneity; hydrology; management; snowpack; spatial scale; water.

Introduction

Snowpack and fire are two critically important ecosystem processes in montane conifer forests of western North America that are highly variable across space (Marshall et al. 2008). Snowpack depth is a major driver of forest productivity, particularly in Mediterranean climate forests of California, where most precipitation falls in the winter (Trujillo et al. 2012). By holding moisture aboveground through the spring and slowly releasing it into the soil, longer snowpack duration can delay peak soil moisture content and lead to increased soil water availability later the growing season (Harpold and Molotch 2015). A persistent winter snowpack also provides important ecosystem services for downstream users, with 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). Under climate change, warmer temperatures will likely cause decreased snowpack depth and earlier snowmelt, particularly at lower elevations and in regions with warmer winters (Stewart et al. 2004, Howat and Tulaczyk 2005, Mote et al. 2005, Stewart 2009, Kapnick and Hall 2010, Harpold and Molotch 2015). However, within a given climate regime, snowpack depth and duration are also influenced by spatial variability in topography (Curtis et al. 2014) and particularly forest cover (Varhola et al. 2010, Lundquist et al. 2013, Harpold et al. 2015), which can create spatial heterogeneity in the depth and duration of snowpack.

Fire is an important driver of forest cover in montane conifer forests (Agee 1993, Sugihara et al. 2006, Safford and Stevens 2017), and thus has the potential to influence snowpack dynamics (Harpold et al. 2014). In more frequent-fire forests, fire maintains a heterogeneous landscape pattern dominated by generally small ($\ll$4 ha) canopy 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, Kane et al. 2014). This heterogeneous landscape structure increases forest resilience to drought, disease, and recurring fires (Larson and Churchill 2012, Safford and Stevens 2017). Forest

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cover and fuel loads in many montane mixed-conifer forests are increasing following more than a century of logging and fire suppression (Safford and Stevens 2017), creating conditions that favor increasingly large patches of high-severity fire with complete loss of forest cover (Miller and Safford 2012, Miller and Quayle 2015). Thus, forests previously characterized by fine-grain heterogeneity may become increasingly characterized by coarse-grain heterogeneity in forest cover (Kane et al. 2014), with uncertain impacts on snowpack and associated hydrological processes (Boisramé et al. 2016).

The effects of forest cover on snowpack are complex (Coughlan and Running 1997, Molotch et al. 2011), and operate at spatial scales ranging from the individual tree to the forest stand (e.g., >1 ha). Evergreen tree canopies intercept falling snow in the winter, 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, which operate at the individual-tree scale, is that initial post-storm snowpack accumulation totals at the forest stand scale are reduced as canopy cover increases, on the order of approximately 4% reductions in snow accumulation per 10% increases in within-stand canopy cover (Varhola et al. 2010), and vice-versa. Greater canopy cover is also associated with slight increases in longwave radiation from trees (Lawler and Link 2011), which can lead to earlier ablation (mass loss) of snowpack under forest canopy than in gaps in some cases, for instance when midwinter ablation rates are primarily determined by air temperature (Lundquist et al. 2013).

However, in other cases, greater canopy cover can reduce snowpack ablation rates by reducing direct shortwave (solar) radiation on the snow surface, reducing air temperatures in the forest understory, and reducing wind speeds and associated turbulent heat fluxes (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 within-stand 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 closure) 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 form, timing, and amount of energy reaching the snowpack surface.

The removal of canopy cover by forest disturbance such as fire (Harpold et al. 2014) or pine beetle outbreaks (Boon 2012) can have counteracting effects on snowpack, by potentially increasing both accumulation and ablation. Thus there remains substantial uncertainty over which of these processes ultimately predominates in determining snowpack duration (Bales et al. 2011*a*). In part, the uncertainty is because the answer to this question depends on a wide range of covarying factors, including but not limited to elevation, temperature, precipitation, slope and aspect, cloudiness (which all influence initial snowfall amounts, sublimation, and melt rates independent of canopy architecture), canopy leaf area index, gap size, and disturbance type (Coughlan and Running 1997, Kershaw 2001, Musselman et al. 2008, Dobrowski 2010, Varhola et al. 2010, Bales et al. 2011*b*, Molotch et al. 2011). This uncertainty is manifest in contradicting results. For instance, Burles and Boon (2011) and Micheletty et al. (2014) found shorter snowpack duration in canopy gaps relative to closed-canopy forest, while Bales et al. (2011*b*), Lundquist et al. (2013), Molotch et al. (2009), and Storck et al. (2002) document instances of longer snowpack duration in canopy gaps relative to closed-canopy forest. 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 dynamics diminishes (Varhola et al. 2010). 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 plot comparisons at a single spatial scale or single burn event, 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.

Given the strong effects of fire on the spatial arrangement of forest cover, there is an urgent need to better understand how variation in fire severity ultimately affects the depth and duration of snowpack via alterations in forest cover at multiple spatial scales. This is especially important during droughts that occur under higher than average temperatures, when reduced snowpack levels and earlier snowmelt can greatly increase physiological stress in trees, and the concurrent risk of wildfire is high (Tague et al. 2009, Allen et al. 2015, Millar and Stephenson 2015). From 2012 to 2015, California experienced a nearly unprecedented four-year drought (Robeson 2015) characterized by record warm temperatures (Griffin and Anchukaitis 2014). During the winter of 2013–2014, the Sierra Nevada snowpack was estimated to be among the 10 lowest peak snowpacks of the past 500 yr (Belmecheri et al. 2016), yet such conditions are expected to become much more common across the region (Mote et al. 2005).

In this paper, I use fine-scale snow survey data from winter 2013–2014, following three recent wildfires in the Sierra Nevada, to investigate the effects of fire severity on snowpack depth at multiple scales. These surveys sampled a range of fire severities and quantified snow depth across multiple site visits, to test the following hypotheses related to the spatial configuration of snowpack on post-fire landscapes: (1) At the individual tree scale, mean snow depth should be greater when overhead canopy cover is absent relative to underneath tree canopies, controlling for the effects of fire severity. (2) At the stand scale (>0.09 ha), mean snow depth should be greatest following low- to moderate-severity fire, where larger canopy gap sizes lead to greater snow accumulation relative to unburned forest while retention of moderate forest canopy cover slows ablation rates relative to more severely burned forest. (3) At a landscape scale, increasing size of contiguous high-severity burn areas should have a negative effect on snow depth, with the opposite size effect in contiguous low-severity burn areas. This paper aims to explicitly disentangle post-fire effects on snowpack at different spatial scales, and contributes important information to ecosystem managers seeking to jointly manage forests and fire for hydrological ecosystem services in dry montane regions.

Methods

Field crews sampled snow depth at three different wildfires in the Sierra Nevada of California during winter 2014 (Fig. 1). The three sites were compositionally and climatically similar, with 2014 being warmer and drier than average at all sites (Table 1). The Angora Fire on the Lake Tahoe Basin burned in 2007 at predominantly high severity within the sampled area, although fuel treatments reduced fire severity in some areas (Safford et al. 2009). Crews sampled snow depth at sample points on a 30-m grid, 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, 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 30-m grid covering 21 ha. The 2012 Reading Fire burned in Lassen Volcanic National Park (where the sampling occurred) and Lassen National Forest, burning over 11,000 ha at a mix of severities (Reading Fire Review 2012). The sampled area included 520 sample points arranged in a 60-m

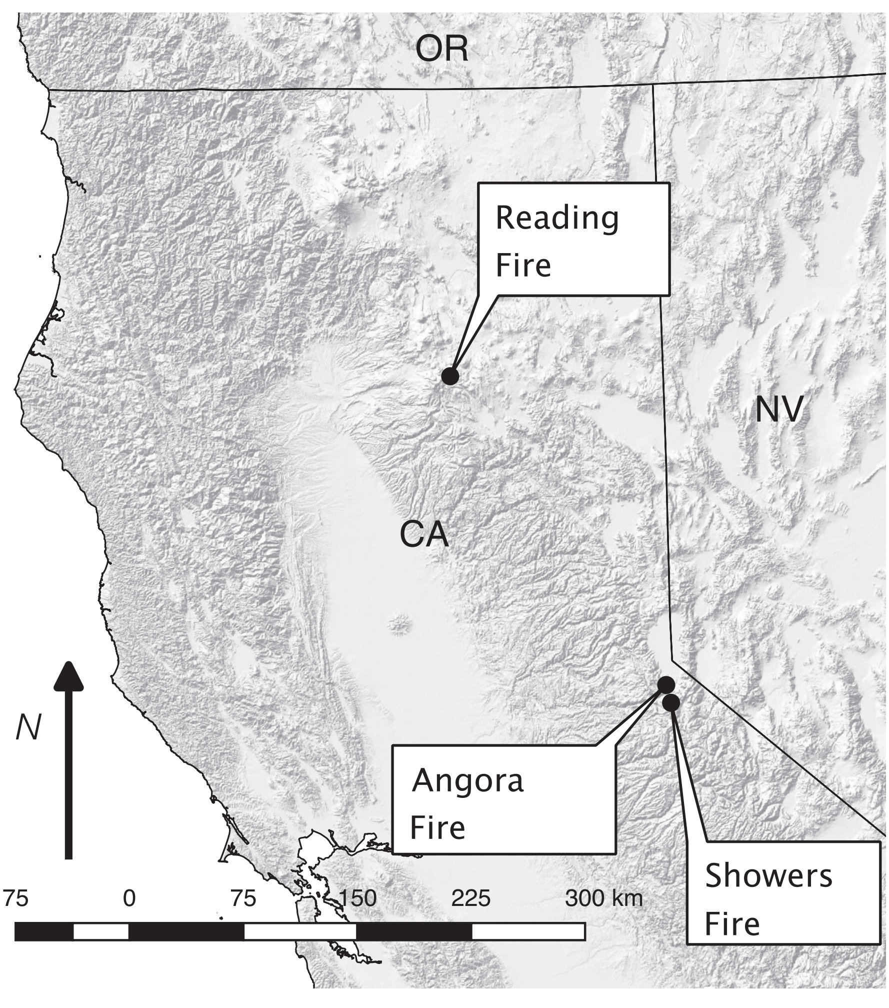

Fig. 1. Map of study locations in northern California, USA.

Table 1. Site and climate descriptions of the three study sites

	Angora	Reading	Showers
Site description			
Coordinates	38.8753° N, −120.0463° W	40.5228° N, −121.4330° W	38.7821° N, −120.0181° W
Elevation (m)	2002	2083	2310
Dominant canopy species†	PIJE, ABCO, ABMA, PICO, CADE	PIJE, ABCO, ABMA, PICO	PIJE, ABMA, ABCO, PICO
Climate data			
Annual mean temperature (°C)	6.60 (1981–2010) 7.92 (2013–2014)	6.70 (1981–2010) 8.49 (2013–2014)	5.9 (1981–2010) 7.42 (2013–2014)
DJF mean temp. (°C)	−0.73 (1981–2010) 1.43 (2013–2014)	−0.63 (1981–2010)2.13 (2013–2014)	−1.23 (1981–2010) 1.37 (2013–2014)
MAM mean temp. (°C)	4.67 (1981–2010) 6.11 (2013–2014)	5.29 (1981–2010)6.78 (2013–2014)	3.53 (1981–2010) 5.00 (2013–2014)
Annual total precipitation (mm)	871.22 (1981–2010) 670.23 (2013–2014)	1539.1 (1981–2010) 962.34 (2013–2014)	1187.61 (1981–2010) 767.25 (2013–2014)
DJF total ppt. (mm)	425.20 (1981–2010) 324.72 (2013–2014)	671.56 (1981–2010) 283.10 (2013–2014)	570.43 (1981–2010) 359.83 (2013–2014)
MAM total ppt. (mm)	227.80 (1981–2010)188.70 (2013–2014)	302.00 (1981–2010)306.07 (2013–2014)	319.02 (1981–2010) 247.20 (2013–2014)

Note: Climatic data are drawn from the PRISM database for the 4-km grid cell overlying the sampling area (www.prism.oregonstate.edu/explorer/). DJF, Dec–Feb; MAM, Mar–May; ppt., precipitation.
†Dominant canopy species in decreasing order of abundance; PIJE, *Pinus jeffreyi*; ABCO, *Abies concolor*; ABMA, *Abies magnifica*; PICO, *Pinus contorta*; CADE, *Calocedrus decurrens*.

grid covering 187 ha. Each sampling effort spanned 2–3 d; 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).

Each site visit was conducted 2–14 d after snowstorms that deposited at least 10 cm of snow, with the exact visit date determined by road conditions, travel time, 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. To measure canopy structure at the individual tree scale, the overhead canopy condition was assessed as either being in a canopy gap, at the drip edge of live canopy, or underneath live canopy of an individual tree (conditions were classified as "open," "edge," and "under"). Aspect at each sample point was classified using a 30-m resolution DEM-derived raster layer, and categorized as "flat" (if slope was <2° from horizontal), "northeast," or "southwest (with breakpoints between the two slope classes at 135° and 315° azimuth). For the 16 April visit to the Reading Fire, crews measured snowpack density in cm^3 using a ProSnow kit (Snowmetrics, Ft. Collins, Colorado, USA), calculated as the density of snow in kg/m^3 of snow volume.

To measure canopy structure at the stand scale, I used burn severity layers from the USDA Forest Service Region 5 for each of the three fires (data *available online*).[4] Severity within the fire perimeter is classified into four severity classes depending on the extent of pre- to post-fire live vegetation change within a given pixel, at a 30-m (0.09-ha) pixel resolution (Miller and Thode 2007). The four fire severity classes are based on composite burn index thresholds, which are associated with percent canopy cover losses of approximately 0% (class 1; unburned/unchanged or very low severity), 1–20% (class 2; low severity), 20–90% (class 3; moderate severity), and >90% (high severity) based on calibrations to field plot data (Miller et al. 2009). The fire severity classification of the 30-m pixel overlapping a given sample point was used as proxy for the degree of canopy cover at the stand scale, while a fifth class (class 0, unburned) was assigned to sampling points outside the fire perimeter. Pixels of a given burn severity class generally occurred in larger contiguous stand-scale "patches" within the burn severity layers (i.e., adjacent pixels with the same classification; Appendix S1: Fig. S1), with patch sizes of a given severity class generally ranging from 1 to 20 ha within the sampling area. Within moderate- and high-severity patches (classes 3 and 4; Appendix S1: Fig. S1), the size of the canopy gaps was generally equivalent to the full size of the moderate/high-severity patch, on the order of 1–20 ha or more. Within unburned stands and very-low-severity patches, the size of the canopy gaps for those

[4] http://www.fs.usda.gov/detail/r5/landmanagement/gis/

sampling points where the overhead canopy condition was "open" was generally much smaller, on the order of 0.01 ha–0.25 ha (*personal observation*).

To test hypotheses 1 and 2 (snow depth response at individual tree scale and stand scale), I constructed a set of linear mixed models that predicted snow depth as a function of three predictors: burn severity class, overhead canopy condition, and aspect, and all possible combinations thereof. Each model included a random intercept for sampling week nested within site, which adjusted the overall model intercept according to the mean snow depth at a given site on a given sampling week (Gelman and Hill 2007). This approach accounts for the fact that the three sites had different amounts of snowfall, with Angora generally less than the other two (Table 1), and that visits were made at varying times following snowfall. Thus, variation in snow depth due to site-level characteristics was accounted for by the random intercepts, and residual variation due to overhead canopy, fire severity, and aspect was accounted for by the fixed-effect coefficients. To account for spatial autocorrelation among sampling points in close proximity, I simulated 1,000 iterations of the model on a subset of the data, sampling 50% of the data points at each site randomly without replacement. I examined the distribution of the model coefficients among these 1,000 samples to evaluate whether conclusions based on the full model are robust to autocorrelation among sampling points.

Models were fit using the lme4 package in R (Bates et al. 2013). I compared all possible combinations of model parameters using the Bayesian Information Criterion (BIC). 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-Roger approximation in the R package pbkrtest (Halekoh and Højsgaard 2014). Because the degrees of freedom in mixed-effects models are difficult to estimate (Bolker et al. 2009), these P values are interpreted cautiously along with evidence from model comparisons and parameter estimates to draw conclusions from the data.

To test hypothesis 3 (landscape-scale effects of patch sizes), I calculated the area of each contiguous patch of each fire severity class for the Reading fire, which had sample points evenly distributed among the four fire severity classes (Appendix S1: Fig. S1). The Angora and Showers fires were predominantly mapped as moderate and high severity, and were lacking in low-severity sample areas, so they were not included for these patch area analyses. I identified contiguous patches of a given severity class by clipping the burn severity layer to the sample area, using a 60-m buffer, and discarding the portions of contiguous burn severity patches that fell outside the sample area. Patches that were less than 60 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 (Appendix S1: Fig. S1). There were 11 very-low-severity patches (mean patch area 10.3 ha), 17 low-severity patches (mean patch area 4.7 ha), 14 moderate-severity patches (mean patch area 7 ha), and 7 high-severity patches (mean patch area 11.6 ha) across the Reading Fire study area. Low-severity patches were always adjacent to very low- and/or moderate-severity patches and moderate-severity patches were always adjacent to low- and/or high-severity patches.

I built a linear mixed-effects regression model with snow depth contingent on (1) the burn severity class at a given sample point, (2) the contiguous patch area of that burn severity class overlapping the sample point, and (3) an interaction between the two variables. To test for different patch area effects depending on burn severity class, I calculated t statistics and associated P values for the interaction coefficient between patch area and each burn severity class, again using the Kenward-Rodgers approximation. I also tested whether variation in snowpack within a given burn severity class was highest in low-severity patches, consistent with a pattern driven by fine-scale heterogeneity in canopy cover driven by low-severity fire. To do this, I calculated the variance in snow depth at the Reading Fire within each severity class for each week, and plotted those values against the sequentially ordered severity classes.

To infer how variation in post-fire canopy cover across the landscape might affect snowpack water storage, I estimated the mean snow water equivalent (SWE) at each sample point in the Reading Fire during week 15 (snowpack sampled on 16 April 2014). Using samples of snowpack density collected from seven snow pits (one at each of seven points within the sampling grid), the mean snowpack density was 439 kg water/m^3 of snowpack. Variability in density was low among sampling points and at different depths in the snowpack (Appendix S1: Table S1; standard deviation among points = 34.9 kg/m^3), suggesting that the snowpack at that date was roughly isothermal and in a period of active melt. I therefore assumed that snowpack density was roughly constant across the landscape, with most landscape variation in SWE being attributable to variation in snow depth (Boon 2012). At each sample point, I calculated the SWE of the snowpack (equivalent depth of water, in m), by multiplying the snowpack depth (in m) by 0.439 (the mean density of snow [439 kg/m^3] divided by the density of water [1,000 kg/m^3]).

To compare the contributions of each of the 13 unique burn-severity–overhead-canopy classes to total site water volume stored in the 15 April snowpack, I first estimated the total snowpack water volume (in m^3) sampled by a given sampling point, by multiplying the SWE at a given sample point by the area represented by that sample point (3,600 m^2, or 0.36 ha). I then summed the snowpack water volume across all sampling points within a given burn-severity–overhead-canopy class, and calculated the proportion of the total water volume across the sampled area (190.8 ha) contributed by each unique burn-severity–overhead-canopy combination. These data are presented to compare relative water storage across the landscape under different canopy conditions, rather than to accurately represent the true volume of water in the snowpack at this location.

Results

The winter of 2014 was characterized by abnormally warm, dry conditions; springtime (March–May) precipitation was closer to 30-yr mean values but temperatures continued to run ~1.5°C above average (Table 1). The winter and spring of 2014 were characterized by numerous rain events at these sites in addition to snowfall events that were measured in this study (*personal observation*). Snowfall events were periodic and interspersed by fairly rapid snowpack ablation (e.g., see Angora Fire, Appendix S1: Fig. S2). Snowpack measurements, which were made 2–14 d after major snowfall events primarily during March and April because of extremely low precipitation in December, January, and February, were therefore likely taken during periods of active ablation (Table 1). A regression of the random effects parameters for sampling week (relativized to the mean site snowfall total across all visits to a given site) against the number of days between snowfall and sampling indicated no significant effect of time since snowfall on the mean snow depth for a given site visit ($t = -1.4$, df = 9, $P = 0.19$).

Overhead canopy cover and stand-scale fire severity both explained variation in snowpack depth (hypotheses 1 and 2). Among fixed-effects parameters, burn severity and aspect each improved model fit in isolation, while overhead canopy alone did not improve model fit over a null model that simply assigned each site visit a single mean snow depth value (Appendix S1: Table S2). However, adding overhead canopy condition to a model that included burn severity substantially improved the fit (ΔBIC = 76; Appendix S1: Table S2). The best model was a full model that included coefficients for burn severity, overhead canopy condition, and aspect, but no interaction terms (Appendix S1: Table S2). Random effects parameters revealed substantial variation among sites and weeks, with Showers generally having the greatest snow depth among the three fires and Angora the least snow depth (Appendix S1: Fig. S2).

Parameter estimates from the full best-fit model indicate that increasing fire severity (at the stand scale) was associated with significantly decreased snow depth (Fig. 2A), controlling for the effects of overhead canopy condition and aspect as well as variation in overall snow depth among site visits (Table 2). 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 (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 individual tree scale, the effect was reversed (Table 2). There was a significant increase in snow depth moving from underneath live tree cover to the canopy edge to a canopy gap (Table 2, Fig. 2B), 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

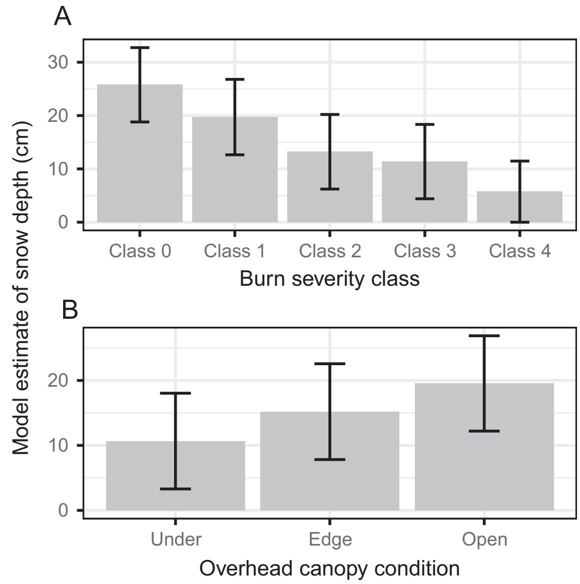

Fig. 2. Model-estimated snow depth among different (A) burn severity classes and (B) overhead canopy gradients. These estimates came from a modified version of the best model, where all variables other than the variable of interest were controlled for by parameterizing as random effects (Appendix S1: Table S2). Error bars represent ± standard error of the fixed effect estimate for each level of the variable of interest.

Table 2. Model output; parameter estimates are from a full model without interactions between terms; parameter estimates indicate effect size of fixed effects relative to the base condition, accounting for variation among sites and among visits.

Altered condition	Parameter estimate (Δ cm)	SE	t	P
Canopy†				
Canopy edge	4.547	1.195	3.805	0.054
Canopy gap	8.945	0.971	9.216	0.008
Fire‡				
Very low severity	−6.149	1.544	−3.982	0.049
Low severity	−12.650	1.106	−11.439	0.005
Moderate severity	−14.555	1.005	−14.485	0.003
High severity	−20.177	1.120	−18.020	0.002
Aspect‡				
Northeast aspect	6.360	0.961	6.620	0.017
Southwest aspect	−3.576	0.916	−3.903	0.051

Note: Altered condition is relative to a base condition of: closed canopy, no fire, flat; snow depth estimate 23.201 ± 11.597 cm (mean ± SE).

† Overhead canopy, a variable defined at the individual tree scale.

‡ Fire severity and aspect are defined at a minimum pixel size of 0.09 ha, but generally occur contiguously at scales of 5–10 ha.

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 less snow depth than flat slopes, but the magnitude of these effects was generally less than the magnitude of canopy and fire effects (Table 2). Parameter estimates were generally robust to spatial autocorrelation, with low variability among models estimated from random subsets of the data (Appendix S1: Fig. S3), and canopy cover, fire severity and aspect effects were consistent across the different fires (Appendix S1: Table S3).

The effect of burn severity patch area on snow depth at the Reading Fire (hypothesis 3) was dependent on which burn severity class a sample point fell into. A model that included an interaction between patch area and burn severity had more support than either a model with burn severity alone (ΔBIC = 3.9) or a model with burn severity and patch area but no interaction (ΔBIC = 12.7). The interaction was primarily driven by the very-low-severity burn class, where the effect of patch area was significantly positive ($t = 4.20$, $P = 0.035$), compared to a negative patch area 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 coefficient for the interaction term between patch area and low-severity burn class was also negative (coefficient = −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 area was 3.4 ha. Regardless of patch area, 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; $R^2 = 0.74$, $t = -4.78$, $P = 0.001$), such that snow depth was much more variable among points in unburned and low-severity classes than in high-severity class, where it was uniformly low.

Despite representing 19% of the total sampled area, the unburned class (class 0) accounted for 57% of the total water volume in snowpack at the sampled portion of the Reading Fire on April 16 (Fig. 5). The unburned and very-low-severity classes combined accounted for 34% of the sampled area but 78% of total water volume within the sampled area on that date (Fig. 5). Within the theoretically "closed canopy" forest of the unburned class, 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. 5). Stand-scale canopy cover estimates for the Reading Fire were 57%, 42%, 25%, 9% and 0%, for fire severity classes 0–4, respectively.

Discussion

This study documents a critical caveat for comparisons of post-fire snowpack between forested sites and canopy gaps: the spatial scale of canopy gaps may determine whether they have deeper, longer-lasting snowpack or shallower, shorter-lasting snowpack compared to forested sites. Consistent patterns of scale-dependent post-fire snowpack dynamics emerged: at the scale of individual trees, canopy cover directly above the sampling point was associated with decreased snowpack depth relative to canopy gaps directly above the sampling point (Fig. 2).

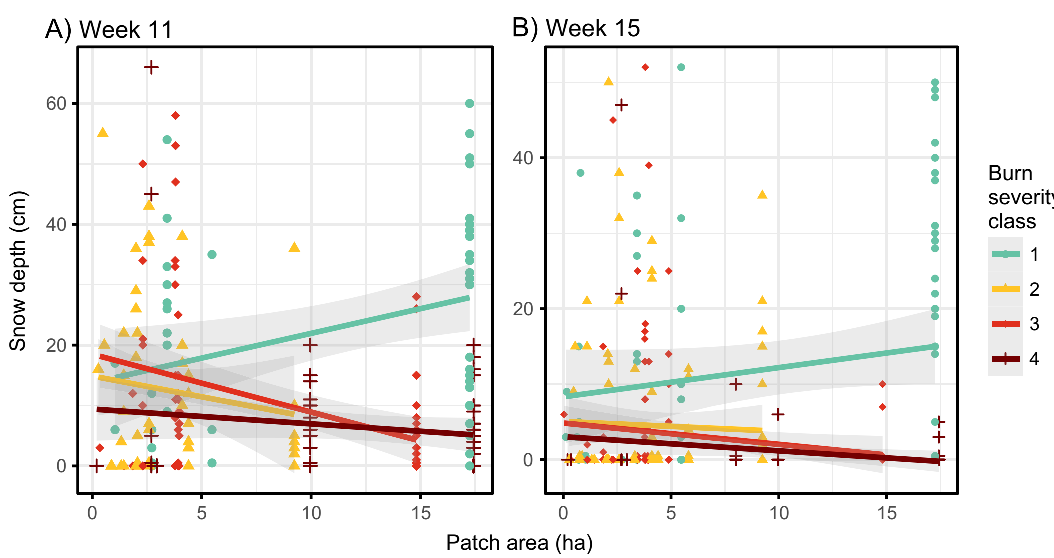

Fig. 3. Patch area effects on snow depth, for two different weeks at the Reading Fire: (A) week 11 and (B) week 15. Points represent individual snow depth measurements, gray bands represent 95% confidence intervals around regression lines. [Color figure can be viewed at wileyonlinelibrary.com]

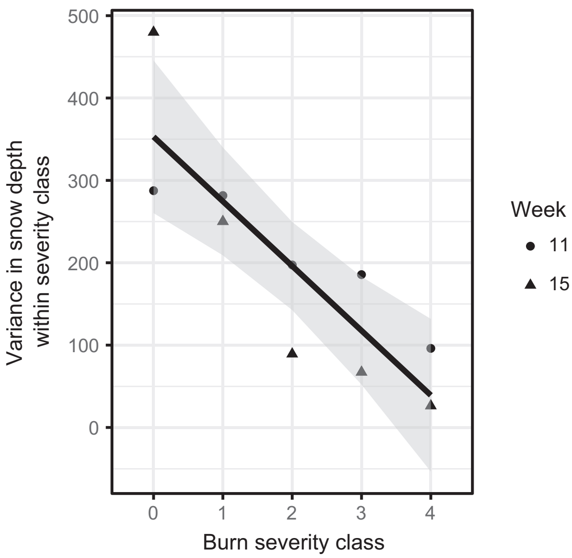

FIG. 4. Variance in snow depth measurements at the Reading Fire, at two different sampling weeks (11 and 15), across the full range of burn severity classes (0 = unburned, 4 = high severity).

However, at the stand scale (generally 1–20 ha resolution), stands with more canopy cover, represented by lower burn severities, were associated with increased snowpack depth relative to stands with less canopy cover (Fig. 2). These results suggest that as the spatial scale of canopy gaps increases, or as forests become more open overall, the predominant control over snowpack depth switches from canopy effects on accumulation, to canopy effects on ablation rates, likely driven by canopy modification of shortwave radiation reaching the snowpack surface (Harpold et al. 2015), although increased turbulent heat transfer and sublimation may also contribute to increased snowpack losses in these larger openings. In other words, when canopy disturbances are larger in scale, the associated increases in snowpack ablation appear to outweigh the increases in snow deposition into these gaps, ablation occurs faster, and snow depths will be shallower than under canopy at most sampling times. This conclusion is supported by the stronger effect sizes of fire severity relative to overhead canopy cover (Table 2), and the negative response of snow depth to increasingly large moderate- and high-severity patch areas (Fig. 3).

The finding that low-severity fire was associated with lower overall snow depth than unburned forest (Fig. 2A) ran counter to hypothesis 1, although the decrease in snow depth at increasingly high severities was expected by hypothesis 1. Data suggest that the unburned forest in these sites may have fairly discontinuous, patchy 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 58% at Showers; these open areas in unburned forests contributed substantially to the total snowpack water storage (Fig. 5). It is possible that the absence of complete canopy cover in unburned forests at each of these sites reflects the legacy of prior disturbance, although none of the unburned areas at these three sites have burned since 1984 (see footnote 4). A more plausible explanation is that all three sites are located east of the Sierra Nevada crest, where productivity decreases and

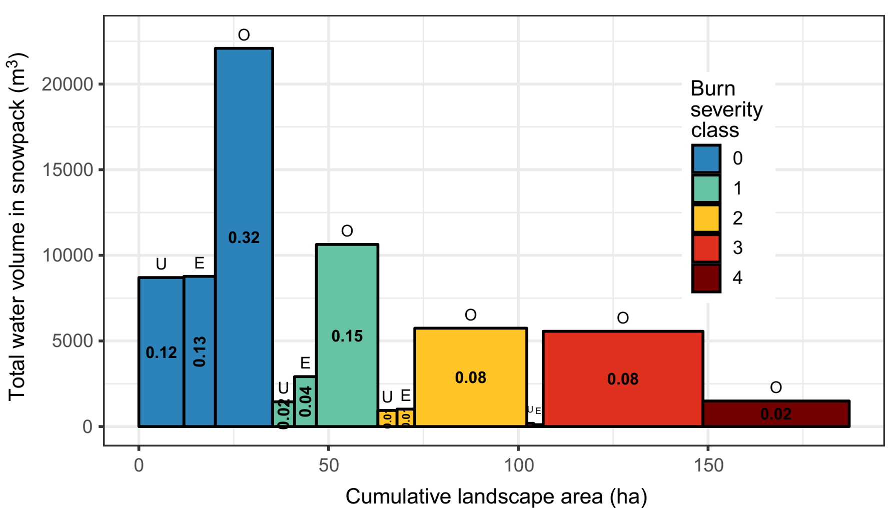

FIG. 5. Cumulative water volume in snowpack across the sampled landscape by burn severity class and overhead canopy condition. Data are from the Reading Fire on 15 April 2014 (Week 15). Bar heights represent total water volume estimated for a given burn-severity–overhead-canopy class. Bar widths indicate the relative area covered by the given class combination. Bar colors represent severity class (0 = unburned, 4 = high severity) and letters above bars represent overhead canopy condition (U = under, E = edge, O = open) within that severity class. The numbers inside the bars represent the proportional contribution of the given class combination to total snowpack water volume across the sampled landscape. [Color figure can be viewed at wileyonlinelibrary.-com]

forests are generally more open, even in the absence of disturbance (Safford and Stevens 2017).

Nonetheless, the difference in snow depth moving from unburned areas to very-low-severity patches at the Reading Fire was substantial: a 15% decrease in canopy cover was associated with a 56% reduction in snow depth. This suggests that there may be a critical threshold of canopy cover at a stand scale (perhaps between the 57% canopy cover found in the unburned condition and the 42% canopy cover found in the very-low-severity class) below which solar radiation exerts a much stronger effect on snow ablation. Interestingly, smaller patches of very-low-severity fire were associated with less snowpack than larger patches (Fig. 3); these smaller patches were generally bordered by low- to moderate-severity patches within close proximity, such that sample points within small patches of very low severity may have been more likely to be close to a patch edge where canopy cover was further reduced (Appendix S1: Fig. S1). Furthermore, the decrease in snowpack in very-low-severity burned areas compared to unburned forest could be partly due to the charred trunks, woody debris, and often abundant needle-cast following fire, which can decrease the snow-surface albedo, increase shortwave absorption and longwave energy inputs to the snowpack, and thereby increase ablation, particularly in the short term after fire (Winkler et al. 2010, Pugh and Small 2012, Gleason et al. 2013). Substantial bark char can be associated with even low-severity post-fire conditions, and can persist for 5–10 yr or more following fire (Stevens et al. 2014). Shrub cover was not directly assessed, but it is possible that increased shrub cover and shrub heights that exceeded the snow depth in burned areas also contributed to increased longwave radiation and ablation relative to unburned areas.

Because snow depth measurements were made periodically on a distributed grid rather than continuously on a snow pillow, the data analyzed here cannot directly inform models of accumulation and ablation rate dynamics, and they do not directly translate to snowpack duration. However, it is very likely that most if not all measurements were made during periods of active melting (Table 1). Despite sampling at elevations and during a season (February–April) when snowpack is generally continuous in the Sierra Nevada (Bales et al. 2011*b*), the snowpack completely dissipated at multiple locations on each fire (Appendix S1: Table S4). This was likely due to the anomalously warm winter temperatures during 2013–2014 (Table 1). Most measurements of density during April at the Reading Fire were consistent across different depths, indicating the snowpack was likely isothermal and actively melting (Appendix S1: Table S1). Thus, although snowpack duration was not directly measured, the observed variation in snowpack depth can be taken as a reasonable indicator that the snow-free date at these sites was likely earlier in high-severity areas, and under closed canopy in low-severity/unburned areas, than it was in canopy gaps in low-severity/unburned areas (Appendix S1: Fig. S2).

The apparent importance of spatial scale of canopy gaps may help explain contradictory results regarding climate-mediation of canopy effects on snowpack dynamics. Lundquist et al. (2013) suggest that snow should last longer in gaps than under canopy in regions that are generally warmer and wetter during the winter; these regions have a more "maritime" snowpack regime characterized by very high accumulations, but also very high melt rates (Trujillo and Molotch 2014). Under such conditions, ablation is driven more by temperature and longwave radiation rather than shortwave (solar) radiation, and thus the shading benefit provided by forest canopy may be less important (Lundquist et al. 2013). However, Harpold et al. (2015) found that snowpack duration was longer under canopy than in gaps at a site in the Jemez Mountains of New Mexico with warmer winters, compared to a site in Colorado with colder winters where snowpack duration was longer in gaps than under canopy. Harpold et al. (2015) note that the forest in the Jemez Mountains was fairly low density and low stature, with rather large canopy gaps, suggesting that the role of longwave radiation in accelerating ablation at warmer sites may be more important at more densely forested sites. The data analyzed here support this hypothesis: had I only measured snow depth within unburned stands, which at the Reading Fire had stand-scale canopy cover of 57% (greater than the 33% canopy cover in the Jemez Mountains), I would have concluded that snow persists longer in gaps than under canopy (Fig. 2B), in line with the prediction of Lundquist et al. (2013). Had I only compared snow depth under trees in unburned stands against snow depth in large gaps created by high-severity fire, which at the Reading Fire had a stand-scale canopy cover of 0%, I would have concluded that snow persists longer under canopy than in gaps (Fig. 2A). Future studies should therefore take care to quantify the spatial scale of the canopy gaps of interest.

The present results are also likely influenced by the anomalously warm, dry winter of 2013–2014, when precipitation totals in the Sierra Nevada were the third-lowest since 1900 (Abatzoglou et al. 2009) and snowpack depth was among the 10 lowest of the past 500 yr (Belmecheri et al. 2016), with April 1 SWE in the Sierra Nevada approximately 20–40% of average.[5] Trujillo and Molotch (2014) describe montane snowpack regimes of western North America as spanning a continuum from maritime regimes with warmer, wetter winters and high accumulation and ablation rates, to continental regimes with cooler, drier winters and lower accumulation and ablation rates. It is less clear how these rates might shift under warmer, drier conditions such as the winter of 2013–2014 in the Sierra Nevada, although these conditions are likely to become more widespread across much of the western United States under climate change (Allen et al. 2015).

The results here suggest that if winters in California continue to be warm and dry, retaining moderate forest

[5] https://cdec.water.ca.gov/cdecapp/snowapp/sweq.action

cover at the stand scale may play an increasingly important role in prolonging snowpack duration by slowing ablation. Given that average winter and spring temperatures at these study sites were >0°C, it is possible that canopy modulation of sensible heat may contribute to prolonged snowpack in more forested areas. Other studies that have sampled canopy effects on snowpack over multiple years have found that ablation rates may influence snowpack duration more in dry years than in wet years, because differences in canopy interception are reduced in dry years (Woods et al. 2006, Molotch et al. 2009). The present study is limited in its ability to distinguish the relative importance of ablation rate vs. interception rate under forest canopy, and the contribution of different components of the snowpack energy budget to the observed patterns of snowpack persistence, because of limited spatial and temporal resolution of snow depth data. Sample grids were spaced far enough apart that they did not capture within-canopy variation in interception by individual trees, nor did they capture gap position or shape, and high-resolution microclimate data was not available. Thus, further high-resolution study of forest–snowpack relations, especially during warm-dry years is warranted.

Beyond the role of climate in mediating the canopy–snowpack relationship, burned forests may affect snowpack and soil moisture dynamics differently than disturbances in unburned forest. As mentioned above, the increase in burnt woody material, needle cast, and low-albedo charring on trunks may accelerate snowpack ablation in burned forests beyond what would be expected from a similar level of disturbance in unburned forests (Gleason et al. 2013). Even if ablation rates increase in large post-fire openings, these areas may still receive increases in overall soil water content, because total snow volume is higher and soils may thaw earlier (Ebel et al. 2012). However, the extra water in larger gaps may not translate to increased tree productivity or forest health if high-severity patches are very large and have few to no surviving trees in them. Furthermore, the duration of soil water storage will largely depend on soil porosity, depth, 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/or eventually lost from the system via stream discharge (Bales et al. 2011*b*). Such losses may heighten the asynchronous supply of and demand for water following fire, both for vegetation, such as naturally regenerating or planted trees, and for downstream human users during the summer growing seasons. This asynchronous supply and demand, in the context of increasingly warm and dry winters, could create a feedback that perpetuates increasingly large disturbances, wherein additional vegetation stress due to low soil moisture in large canopy gaps increases the likelihood of future fires, which would continue to expand the sizes of gaps and depress soil moisture via early snowmelt (Millar and Stephenson 2015).

Provision of water, in the form of snowpack, is a valuable ecosystem service provided by montane forests (Mote et al. 2005). 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. 2011*a*). 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. 2011*a*). For drier, fire-prone, less productive forests, 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 deepest snowpack, although this was facilitated by 37–53% canopy openness among the three fires studied. A completely closed-canopy forest would be likely to exhibit reduced snowpack duration and volume relative to a partially open forest, because of the negative effect of overhead canopy cover on snowpack accumulation. Closed-canopy forests also have higher likelihood of burning at high severity when they do eventually burn (McKelvey et al. 1996, Fulé et al. 2004).

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 stand-scale snowpack duration. There is strong evidence that fine-scale heterogeneity within a forest stand, where tree cover is highly variable within 5–20 ha areas, was a common historical condition in mixed-conifer forests of the Sierra Nevada and other regions in the western United States, and that this heterogeneity provided a range of other valuable services, including habitat diversity for wildlife and resilience to large-scale stand-replacing fire (Lydersen and North 2012, Lydersen et al. 2013, Kane et al. 2014, Safford and Stevens 2017). The data presented here suggest that snowpack provisioning may be another benefit to increasing and maintaining stand-scale canopy heterogeneity in forests that currently have homogenously high canopy cover, through a combination of fuel reduction treatments, prescribed fire, and managed wildfire. However, some untreated forests may currently be configured to maximize stand-scale snowpack duration. 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.

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Literature Cited

Abatzoglou, J. T., K. T. Redmond, and L. M. Edwards. 2009. Classification of regional climate variability in the state of California. Journal of Applied Meteorology and Climatology 48:1527–1541.

Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., USA.

Allen, C. D., D. D. Breshears, and N. G. McDowell. 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere 6:art129.

Bales, R. C., J. J. Battles, Y. Chen, M. H. Conklin, E. Holst, K. L. O'Hara, P. Saksa, and W. Stewart. 2011*a*. Forests and water in the Sierra Nevada: Sierra Nevada watershed ecosystem enhancement project. Sierra Nevada Research Institute Report number 11.1. https://eng.ucmerced.edu/snri/files/public/SWEEP_published_112911.pdf

Bales, R. C., J. W. Hopmans, A. T. O'Geen, M. Meadows, P. C. Hartsough, P. Kirchner, C. T. Hunsaker, and D. Beaudette. 2011*b*. Soil moisture response to snowmelt and rainfall in a Sierra Nevada mixed-conifer forest. Vadose Zone Journal 10: 786–799.

Bates, D. M., M. Maechler, B. M. Bolker, and S. Walker. 2013. lme4: Linear mixed-effects models using Eigen and S4. R package version 1.0-5. CRAN.R-project.org/package=lme4

Belmecheri, S., F. Babst, E. R. Wahl, D. W. Stahle, and V. Trouet. 2016. Multi-century evaluation of Sierra Nevada snowpack. Nature Climate Change 6:2–3.

Boisramé, G., S. Thompson, B. Collins, and S. Stephens. 2016. Managed wildfire effects on forest resilience and water in the Sierra Nevada. Ecosystems 20:717–732.

Bolker, B. M., M. E. Brooks, C. J. Clark, S. W. Geange, J. R. Poulsen, M. H. H. Stevens, and J.-S. S. White. 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends in Ecology & Evolution 24:127–135.

Boon, S. 2012. Snow accumulation following forest disturbance. Ecohydrology 5:279–285.

Burles, K., and S. Boon. 2011. Snowmelt energy balance in a burned forest plot, Crowsnest Pass, Alberta, Canada. Hydrological Processes 25:3012–3029.

Coughlan, J. C., and S. W. Running. 1997. Regional ecosystem simulation: A general model for simulating snow accumulation and melt in mountainous terrain. Landscape Ecology 12:119–136.

Curtis, J. A., L. E. Flint, A. L. Flint, J. D. Lundquist, B. Hudgens, E. E. Boydston, and J. K. Young. 2014. Incorporating cold-air pooling into downscaled climate models increases potential refugia for snow-dependent species within the Sierra Nevada ecoregion, CA. PLoS One 9: e106984.

Dobrowski, S. Z. 2010. A climatic basis for microrefugia: the influence of terrain on climate. Global Change Biology 17:1022–1035.

Ebel, B. A., E. S. Hinckley, and D. A. Martin. 2012. Soil-water dynamics and unsaturated storage during snowmelt following wildfire. Hydrology and Earth System Sciences 16:1401–1417.

Fulé, P. Z., J. E. Crouse, A. E. Cocke, M. M. Moore, and W. W. Covington. 2004. Changes in canopy fuels and potential fire behavior 1880–2040: Grand Canyon, Arizona. Ecological Modelling 175:231–248.

Gelman, A., and J. Hill. 2007. Data analysis using regression and multilevel/hierarchical models. Cambridge University Press, New York, New York, USA.

Gleason, K. E., A. W. Nolin, and T. R. Roth. 2013. Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation. Geophysical Research Letters 40:4654–4661.

Griffin, D., and K. J. Anchukaitis. 2014. How unusual is the 2012–2014 California drought? Geophysical Research Letters 41:9017–9023.

Halekoh, U., and S. Højsgaard. 2014. A Kenward-Roger approximation and parametric bootstrap methods for tests in linear mixed models—The R package pbkrtest. Journal of Statistical Software 59:1–30.

Harpold, A. A., and N. P. Molotch. 2015. Sensitivity of soil water availability to changing snowmelt timing in the western U.S. Geophysical Research Letters 42:8011–8020.

Harpold, A. A., J. A. Biederman, K. Condon, M. Merino, Y. Korgaonkar, T. Nan, L. L. Sloat, M. Ross, and P. D. Brooks. 2014. Changes in snow accumulation and ablation following the Las Conchas forest fire, New Mexico, USA. Ecohydrology 7:440–452.

Harpold, A. A., N. P. Molotch, K. N. Musselman, R. C. Bales, P. B. Kirchner, M. Litvak, and P. D. Brooks. 2015. Soil moisture response to snowmelt timing in mixed-conifer subalpine forests. Hydrological Processes 29:2782–2798.

Howat, I. M., and S. Tulaczyk. 2005. Trends in spring snowpack over a half-century of climate warming in California, USA. Pages 151–156 *in* D. R. MacAyeal, editor. Annals of glaciology. Volume 40. International Glaciological Society, Cambridge, UK.

Hunsaker, C. T., T. W. Whitaker, and R. C. Bales. 2012. Snowmelt runoff and water yield along elevation and temperature gradients in California's southern Sierra Nevada. JAWRA Journal of the American Water Resources Association 48:667–678.

Kane, V. R., M. P. North, J. A. Lutz, D. J. Churchill, S. L. Roberts, D. F. Smith, R. J. McGaughey, J. T. Kane, and M. L. Brooks. 2014. Assessing fire effects on forest spatial structure using a fusion of Landsat and airborne LiDAR data in Yosemite National Park. Remote Sensing of Environment 151:89–101.

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

Kershaw, G. P. 2001. Snowpack characteristics following wildfire on a simulated transport corridor and adjacent subarctic forest, Tulita, NWT, Canada. Arctic Antarctic and Alpine Research 33:131–139.

Larson, A. J., and D. Churchill. 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. Forest Ecology and Management 267:74–92.

Lawler, R. R., and T. E. Link. 2011. Quantification of incoming all-wave radiation in discontinuous forest canopies with application to snowmelt prediction. Hydrological Processes 25:3322–3331.

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 49:6356–6370.

Lydersen, J., and M. North. 2012. Topographic variation in structure of mixed-conifer forests under an active-fire regime. Ecosystems 15:1–13.

Lydersen, J. M., M. P. North, E. E. Knapp, and B. M. Collins. 2013. Quantifying spatial patterns of tree groups and gaps in mixed-conifer forests: Reference conditions and long-term changes following fire suppression and logging. Forest Ecology and Management 304:370–382.

Marshall, J. D., J. M. Blair, D. P. C. Peters, G. Okin, A. Rango, and M. Williams. 2008. Predicting and understanding ecosystem responses to climate change at continental scales. Frontiers in Ecology and the Environment 6:273–280.

McKelvey, K. S., C. N. Skinner, C. Chang, D. C. Erman, S. J. Hussari, D. J. Parsons, J. W. van Wagtendonk, and C. P. Weatherspoon. 1996. An overview of fire in the Sierra Nevada. University of California, Centers for Water and Wildland Resources, Davis, California, USA.

Micheletty, P. D., A. M. Kinoshita, and T. S. Hogue. 2014. Application of MODIS snow cover products: wildfire impacts on snow and melt in the Sierra Nevada. Hydrology and Earth System Sciences 18:4601–4615.

Millar, C. I., and N. L. Stephenson. 2015. Temperate forest health in an era of emerging megadisturbance. Science 349:823–826.

Miller, J. D., and B. Quayle. 2015. Calibration and validation of immediate post-fire satellite derived data to three severity metrics. Fire Ecology 11:12–30.

Miller, J. D., and H. Safford. 2012. Trends in wildfire severity 1984–2010 in the Sierra Nevada, Modoc Plateau and southern Cascades, California, USA. Fire Ecology 8:41–57.

Miller, J. D., and A. E. Thode. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta normalized burn ratio (dNBR). Remote Sensing of Environment 109:66–80.

Miller, J. D., E. E. Knapp, C. H. Key, C. N. Skinner, C. J. Isbell, R. M. Creasy, and J. W. Sherlock. 2009. Calibration and validation of the relative differenced normalized burn ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. Remote Sensing of Environment 113:645–656.

Molotch, N. P., P. D. Brooks, S. P. Burns, M. Litvak, R. K. Monson, J. R. McConnell, and K. Musselman. 2009. Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests. Ecohydrology 2:129–142.

Molotch, N. P., P. D. Blanken, and T. E. Link. 2011. Snow: hydrological and ecological feedbacks in forests. Pages 541–555 *in* D. F. Levia, D. CarlyleMoses, and T. Tanaka, editors. Forest hydrology and biogeochemistry: synthesis of past research and future directions. Springer, New York, New York, USA.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86:39–49.

Musselman, K. N., N. P. Molotch, and P. D. Brooks. 2008. Effects of vegetation on snow accumulation and ablation in a mid-latitude sub-alpine forest. Hydrological Processes 22:2767–2776.

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.

Pomeroy, J., X. Fang, and C. Ellis. 2012. Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. Hydrological Processes 26:1892–1905.

Pugh, E., and E. Small. 2012. The impact of pine beetle infestation on snow accumulation and melt in the headwaters of the Colorado River. Ecohydrology 5:467–477.

Reading Fire Review. 2012. Lassen National Park, Mineral King, California, USA. http://www.nps.gov/lavo/learn/management/upload/Reading-Fire-Review.pdf

Rice, R., and R. C. Bales. 2010. Embedded-sensor network design for snow cover measurements around snow pillow and snow course sites in the Sierra Nevada of California. Water Resources Research 46:W03537. http://onlinelibrary.wiley.com/doi/10.1029/2008WR007318/full

Robeson, S. M. 2015. Revisiting the recent California drought as an extreme value. Geophysical Research Letters 42:6771–6779.

Safford, H. D., and J. T. Stevens. 2017. Natural range of variation (NRV) for yellow pine and mixed conifer forests in the Sierra Nevada, southern Cascades, and Modoc and Inyo National Forests, California. General Technical Report PSW-GTR-256. USDA Forest Service, Pacific Southwest Research Station, Albany, California, USA.

Safford, H. D., D. A. Schmidt, and C. H. Carlson. 2009. Effects of fuel treatments on fire severity in an area of wildland-urban interface, Angora Fire, Lake Tahoe Basin, California. Forest Ecology and Management 258:773–787.

Schlenker, W., W. M. Hanemann, and A. C. Fisher. 2007. Water availability, degree days, and the potential impact of climate change on irrigated agriculture in California. Climatic Change 81:19–38.

Seibert, J., J. J. McDonnell, and R. D. Woodsmith. 2010. Effects of wildfire on catchment runoff response: a modelling approach to detect changes in snow-dominated forested catchments. Hydrology Research 41:378–390.

Stevens, J. T., H. D. Safford, and A. M. Latimer. 2014. Wildfire-contingent effects of fuel treatments can promote ecological resilience in seasonally dry conifer forests. Canadian Journal of Forest Research 44:843–854.

Stewart, I. T. 2009. Changes in snowpack and snowmelt runoff for key mountain regions. Hydrological Processes 23:78–94.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2004. Changes in snowmelt runoff timing in western North America under a "business as usual" climate change scenario. Climatic Change 62:217–232.

Storck, P., D. P. Lettenmaier, and S. M. Bolton. 2002. Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. Water Resources Research 38:1223. http://onlinelibrary.wiley.com/doi/10.1029/2002WR001281/full

Sugihara, N. G., J. W. van Wagtendonk, K. E. Shaffer, J. Fites-Kaufman, and A. E. Thode. 2006. Fire in California's ecosystems. University of California Press, Berkeley, California, USA.

Tague, C., K. Heyn, and L. Christensen. 2009. Topographic controls on spatial patterns of conifer transpiration and net primary productivity under climate warming in mountain ecosystems. Ecohydrology 2:541–554.

Trujillo, E., and N. P. Molotch. 2014. Snowpack regimes of the Western United States. Water Resources Research 50:5611–5623.

Trujillo, E., N. P. Molotch, M. L. Goulden, A. E. Kelly, and R. C. Bales. 2012. Elevation-dependent influence of snow accumulation on forest greening. Nature Geoscience 5:705–709.

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.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313:940–943.

Winkler, R., S. Boon, B. Zimonick, and K. Baleshta. 2010. Assessing the effects of post-pine beetle forest litter on snow albedo. Hydrological Processes 24:803–812.

Woods, S. W., R. Ahl, J. Sappington, and W. McCaughey. 2006. Snow accumulation in thinned lodgepole pine stands, Montana, USA. Forest Ecology and Management 235:202–211.

Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1575/full

Data Availability

Data available from the Zenodo Repository: https://doi.org/10.5281/zenodo.574108