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Estimating evapotranspiration change due to forest treatment and fire at the basin scale in the Sierra Nevada, California

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Abstract

We investigated the potential magnitude and duration of forest evapotranspiration (ET) decreases resulting from forest-thinning treatments and wildfire in west-slope watersheds of the Sierra Nevada range in California, U.S.A. using a robust empirical relation between Landsat-derived mean-annual normalized difference vegetation index (NDVI) and ET measured at flux towers. Among forest treatments, the minimum observed NDVI change required to produce a significant departure from control plots with NDVI of about 0.70 was -0.09 units, corresponding to a basal-area reduction of 29.1 m^2 ha^{-1} (45% reduction) and equivalent to an estimated ET reduction of 153 mm yr^{-1} (21% change; approximate mean annual precipitation = 1000 mm). Intensive thinning in highly productive forests that approached pre-fire-exclusion densities reduced basal area by 40-50%, generating estimated ET reductions of 153-218 mm yr^{-1} (21-27% change) over five years following treatment. Low-intensity underburn treatments resulted in no significant change in ET. Examining the cumulative impact of wildfires on ET between 1990 and 2008, we found that the lower and wetter American River basin (5310 km^2) generated more than twice the ET reduction per unit area than those in the higher and drier Kings River basin (4790 km^2), corresponding to greater water and energy limitations in the latter and greater fire severity in the former. A rough extrapolation of these results to the entire American River watershed suggests that ET reductions due to forest thinning by wildfire could approach 10% of full natural flows for dry years and 5% over all years.

Keywords: Water balance, forest evapotranspiration, forest thinning, forest fire, Sierra Nevada

1. Introduction

Many western forests are overstocked with live trees, a legacy of successful fire-exclusion policies since the 1920's (Agee & Skinner, 2005; Miller et al., 2012). In areas where fire previously burned every decade or two, forests transitioned from mosaics of forested stands and open areas, to areas of continuous canopy cover (Collins et al., 2011; Scholl & Taylor, 2010; Taylor, 2004). This, in turn, has led to increased susceptibility to stand-replacing fires, disease and insect attacks, and increased mortality (Allen, 2007). Implementing a policy of forest thinning using both mechanical treatments and management fire will be essential to managing for ecosystem resilience to climate warming (North et al., 2015), including reduced fire risk and potential changes in water yield (Hopkinson & Battles, 2015; Troendle et al., 2007).

The multi-year California drought that began in fall 2011 highlighted the need to re-examine earlier estimates of water consumption by overstocked forests versus less-dense and healthier forests (e.g. Huff et al., 2000; Kattelmann et al., 1983). There is substantial consensus that forest thinning above a certain threshold reduces evapotranspiration (ET) and increases runoff. Bosch and Hewelet (1982), Stednick (1996), and Brown (2005) demonstrated that changes in forest density of greater than approximately 20% cause measureable changes in forest water balance. Interpreting the results of such experiments has been hindered by limited treatment extents compared to the large adjacent untreated watershed area tributary to the same runoff measurement. Other challenges included a lack of repeat or follow-up treatments such as underburns to sustain the impact of the initial treatment by limiting understory growth and reducing the seed bank of trees and shrubs. And finally, because many studies depend on reference watersheds, the adequacy of matched watersheds is a substantial source of uncertainty when interpreting results.

Relating ET magnitude and its temporal trend to measures of forest change due to fire or mechanical treatment such as leaf area index, canopy cover, and basal area provides a powerful tool for evaluating ET change at broad scales (e.g. Vanderhoof & Williams, 2015) as well as providing a means of estimating benefits to forest health such as improved water availability for trees or instream flows. The recent Sierra Nevada Adaptive Management Project (SNAMP) project is a good example of such an endeavor, though limited treatment areas confounded by drought in 2012-2016 narrowed the conclusions that could be definitively drawn from this research (Fry et al., 2015). Headwater-catchment modeling results extending from this work suggest that runoff in the Central Sierra Nevada could be increased 12% over 20 years with vegetation thinning by 8%, and over 50% if fire reduced vegetation by 40% (Conklin et al., 2015; Saksa et al., 2017). A complementary approach to estimating change in forest evapotranspiration is to use remotely sensed information to calculate ET directly (Mu et al., 2011) or indirectly using vegetation indices as they relate to measured ET (Goulden et al., 2012).

Data-driven remote-sensing measurements of forest evapotranspiration provide a valuable means of quantifying temporal and spatial variability before and following forest-canopy thinning. Goulden et al. (2012) demonstrated a high correlation between annual evapotranspiration and annual average of the MODIS satellite-derived normalized differenced vegetation index (NDVI); and this relationship also compared favorably with annual mass-balance estimates at the river basin scale (precipitation minus runoff) at an annual resolution. A second important outcome of this work was the demonstration that ET variability is substantially less than precipitation and runoff, arguing that changes in ET are driven largely by changes in vegetation. This method of calculating ET is particularly powerful because it does not require additional parameters such as soil properties and moisture as with many mechanistic models, which are often not available at broad scales. Given that the methods of Goulden et al (2012) and the subsequent application (Goulden & Bales, 2014) provide a robust means of estimating ET in the Sierra Nevada, we sought to analyze temporal and spatial variability of ET change in areas of known forest disturbance.

In this paper, we first estimated changes in forest water use due to changes in forest density caused by mechanical treatment or wildfire at the plot or individual fire scale and then examined the cumulative potential impacts of wildfires on ET at the watershed scale. We determined magnitude and duration of ET change after forest treatments and fire across a range of elevations and latitudes within California’s Sierra Nevada. We focused on two primary research questions. First, what is the range and variability of NDVI change associated with forest treatments and forest fire in representative watershed areas? Second, what is the potential range and scale of ET reduction due to forest treatments and forest fires? We conclude with a discussion of further research needed to more rigorously extend this analysis to the full watershed scale.

2. Methods

The study area encompasses the central Sierra Nevada, including the lower-elevation, wetter and warmer American River basin, the higher-elevation, drier and colder Kings River basin (southern Sierra Nevada), and forest-treatment areas between these watersheds (Figure 1). We focused on four treatment areas (Figure 1a, b, c), as well as burned and unburned areas over the entire American and Kings River watersheds during the 1990-2008 period (Figure 1a, d, e). We examined NDVI change, measured using Landsat surface-reflectance data, and subsequently calculated ET as described in the following paragraphs.

In order to estimate ET changes at the forest-patch scale (1-100 ha), we first established a relation between point measurements of evapotranspiration and remotely sensed NDVI. NDVI maximizes the contrast between strong

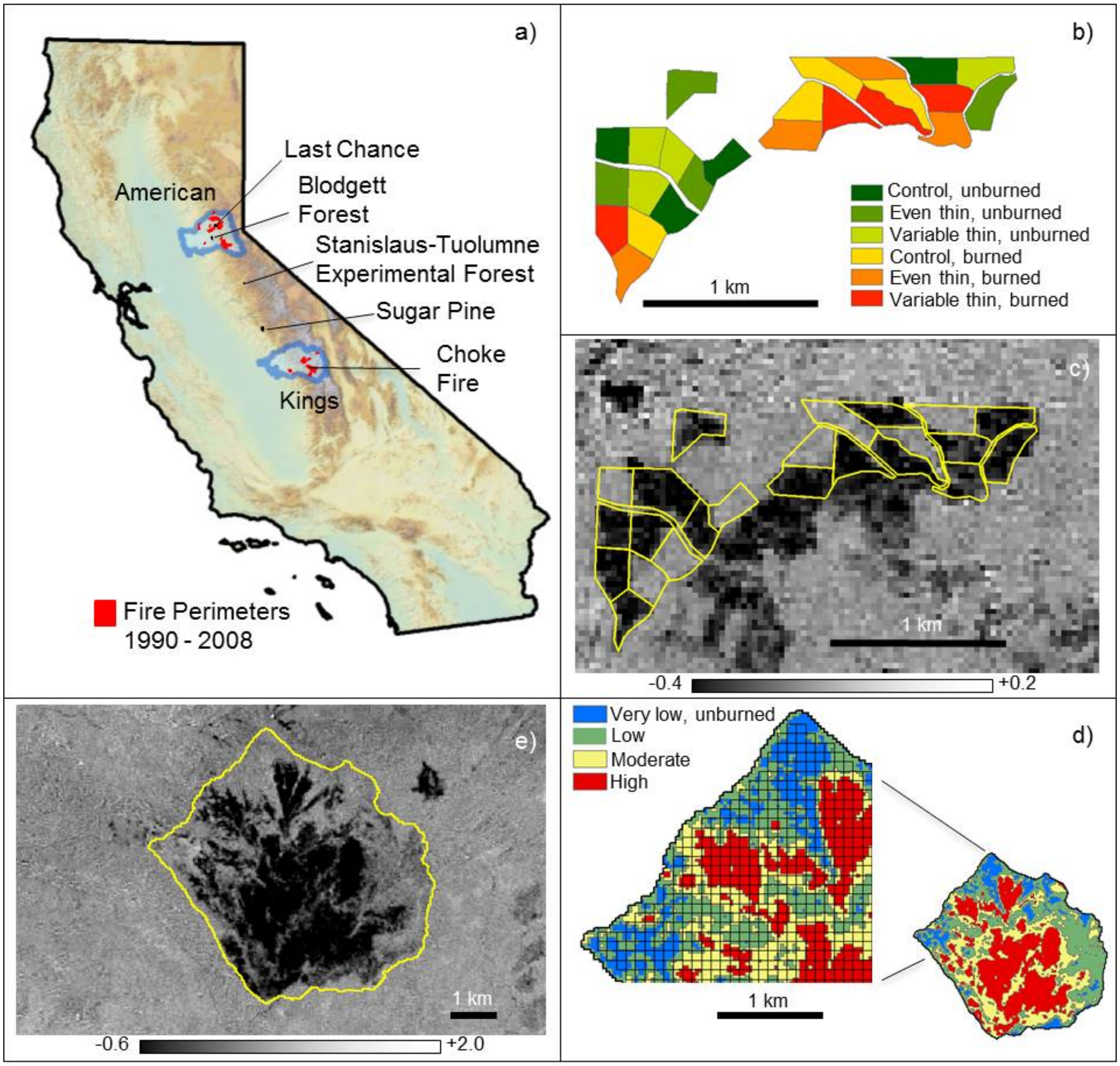

Figure 1. Location of forest fires and treatments examined in this study within California, USA, clockwise from top left: a) overview map showing all fires in the American and Kings watersheds for the 1990-2008 period as well as selected forest treatment areas, b) experimental forest thinning treatment design for the Stanislaus-Tuolumne Experimental Forest Variable Thinning Project (STEF), c) NDVI change at STEF between July 22, 2010 and July 30, 2013, pre- and post-treatment, d) perimeter and burn severity of the 1997 Choke Fire (lower right) and an expanded region of the fire that illustrates the 90-m polygon mesh used to sample Landsat NDVI imagery, and e) NDVI change of Choke Fire between July 24, 1996 and July 30, 1998.

absorbance of red light by chlorophyll and weaker absorbance and scattering of near-infrared light by healthy foliage. Goulden et al. (2012) demonstrated that annual in-situ ET measurements at flux towers were well correlated with NDVI derived from 250-m resolution MODIS satellite data. Here, we use a similar relation between measured ET and higher-spatial-resolution Landsat data, which offers a 30-m resolution and low image-to-image alignment error (generally less than half a pixel). This higher resolution is ideal for examining NDVI change at the scale of typical forest treatments (Figure 1c) and also for examining highly heterogeneous changes caused by forest fire (Figure 1e).

Figure 2 depicts the primary ET-NDVI relation used in this analysis. Regression data were comprised of water-year annual evapotranspiration (water year is October 1 to September 30) from ten flux towers located in the Sierra Nevada and Southern California from 2007 to 2016 (see Goulden et al., 2012). Taken together, this data set represents 78 water years. These observations were stratified by impacts to the forest patch contributing to each flux tower. A point was classified as drought affected if PRISM annual precipitation (PRISM Climate Group, 2012) for the 800-m grid cell encompassing the flux tower was below the 1981-2010 PRISM average for the site. Other classifications pertained to potential changes to the forest structure due to thinning or fire as well as whether this occurred in association with drought conditions.

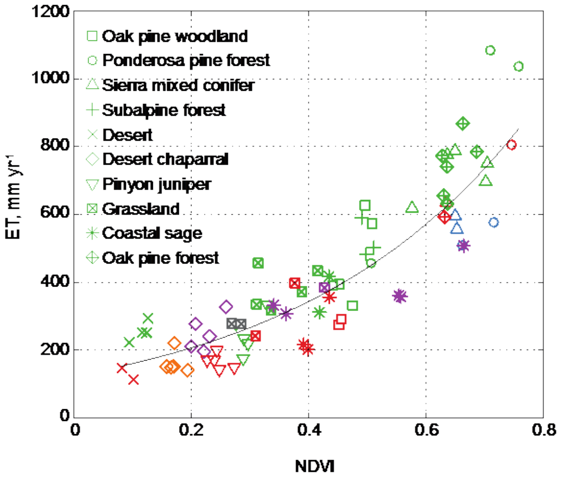

Figure 2. Annual water year evapotranspiration (ET) at ten flux towers versus annual average Landsat-derived normalized difference vegetation index (NDVI) for upwind contributing areas at each location for water years 2007-2016. Point colors represent impacts to vegetation at each site as follows: none (green), drought (red), drought and management action (blue), fire (purple), drought and fire (orange), and management action (grey). See text for a more complete description. Best fit regression for all years is ET (mm yr^{-1}) = 123.8243 × e$^{(2.5456 \times \mathrm{NDVI})}$, where NDVI ranges from 0 to 1 (R^2 = 0.7917 for ln(ET) results). For information on the flux towers used, see Goulden et al. (2012).

We calculated annual mean NDVI from the complete collection of U.S. Geological Survey Landsat Surface Reflectance data (Masek et al., 2006) for the water years of interest following these steps:

1. Determine mean NDVI value in the area of interest for each date. This was accomplished by uploading a Keyhole Markup Language (kml) file of all polygons of interest to a Google fusion file and determining the mean NDVI in Google Earth Engine (Google Earth Engine Team, 2015). Full U.S. Geological Survey Landsat Surface Reflectance collections are available within the Google Earth Engine environment. Specific Landsat tiles were chosen using the World Wide Reference System 2 for each area of analysis to minimize the possible influence of different viewing angles between Landsat paths. We used Path 43 and Row 33 for areas in the American River watershed and the Stanislaus-Tuolumne Experimental Forest, and Path 42 and Rows 34 and 35 for the Kings River watershed and Sugar Pine treatment area. This resulted in approximately 900 available images for analysis of each polygon from 1984 through 2016. NDVI was calculated from bands 3 and 4 for Landsat 5 and 7, and bands 4 and 5 for Landsat 8. Pixels were filtered using the Landsat Collection-1 Level-1 Quality-Assessment (QA) Band (CFMask, Foga et al., 2017) removing all pixels with possible clouds, cloud shadows, or snow contamination. NDVI values were further constrained to a range of 0.2 and 1.0 in order to remove largely unvegetated areas from the analysis (Carlson et al., 1990).
2. Homogenize Landsat Thematic Mapper (Landsat 5 or LT-5) and Landsat Operational Land Imager (Landsat 8 or LC8) values to Landsat Enhanced Thematic Mapper values (Landsat 7 or LE-7) using the following equations (Su et al., 2017, Figure S3):

$$NDVI_{Landsat5\_homogenized} = NDVI_{Landsat5} \times 1.1307 - 0.0571$$

$$NDVI_{Landsat8\_homogenized} = NDVI_{Landsat8} \times 0.9938 - 0.0167$$

3. Temporally interpolate the data. First, smooth the resultant time series using a centered moving average spanning five observation dates. Then, determine the mid-month value for all months by interpolating between smoothed points. Finally, average mid-month values between October 1st and September 30th of the subsequent year to obtain water-year NDVI average values.

Smoothing and month centering reduced the impact of the discontinuous availability of Landsat data due to its 8- and 16-day overpass frequency and excluded data during winter due to clouds and snow. We used a similar process for determining annual NDVI in forest-treatment plots and burned areas, as described in the following paragraphs.

We examined select forest treatments spanning the latitudinal range between the American and Kings River basins on the west slope of the Sierra Nevada range (Figure 1a, b). Forest-treatment data available for this study from north to south were from the Sierra Nevada Adaptive Management Project (SNAMP) Last Chance fireshed treatment area, select treatment compartments in the Blodgett Experimental Forest, the variable-density thinning project at the Stanislaus-Tuolumne Experimental Forest (Figure 1b, c), and the SNAMP Sugar Pine fireshed treatment area. Treatments in these forests were well documented and represent a range of treatment intensity (Table S1). Last Chance treatments burned by the 2013 American fire were excluded from analysis because our focus was on the effect of treatments. For each treatment, we estimated NDVI change by averaging the five years prior to treatment and comparing this to the five years post treatment for treated and control units. The significance of the observed change was determined using the before-after-control-impact (BACI) assessment (Stewart-Oaten et al., 1986) as applied by Fry et al, 2015. This entailed a two-way ANOVA on treated and control plots before and after treatment with change detection determined by the interaction between treatment type and before-after classification at the 95% confidence level (Smith, 2002). Change detection on control plots before and after treatment was determined using a two-sample paired t-test. In order to characterize the general climate for the region, we calculated mean water-year precipitation and temperature using monthly 4-km resolution PRISM data (PRISM Climate Group, 2012). The averaging area covered the full latitude range of our study sites and included the American, Mokelumne, Stanislaus, Tuolumne, Merced, San Joaquin, and Kings watersheds above their Sierra-foothill dams.

We examined the role of fire on ET change by using fire-severity data and estimated changes in canopy cover and basal area from the USFS Monitoring Trends in Burn Severity (MTBS, Eidenshink et al., 2007; http://www.mtbs.gov) and Miller et al. (2009; https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=STELPRDB5327833) geodatabases. We selected all forest fires in the American and Kings watersheds between 1990 and 2008, excluding those fires at lower elevations in largely unforested areas of the watersheds. The date range chosen included five years of baseline NDVI data prior to the first fire and five years after the last fire, and avoided the extreme forest mortality of the California drought (2012-2015) and associated large fires (the American (2013) and Rough (2015)) in these watersheds. In order to examine effects by severity, we used 1-year post-fire severity classification polygons from the MTBS database directly and applied an area-weighted mean of severity classes to determine average NDVI-change within an individual fire perimeter.

In order to assess the role of elevation on NDVI change after fire, we created a 90-m mesh over each fire area assigning each 1800 m^2 polygon an elevation based on the 30-m Shuttle Radar Topography Mission elevation dataset (Farr et al., 2007). The mesh was created within a buffer of 75 m inside the fire perimeter to avoid sampling unburned areas (Figure 1d). Additionally, we created a set of randomly selected square 90-m polygons in areas that remained unburned between 1990 and 2008 that accounted for approximately 20% of each watershed area. Annual NDVI values were determined for all polygons for the period 1985-2013 and burned-area polygons records were summarized as 5-year pre-fire mean NDVI, 1-year post-fire NDVI, and 5-year post-fire mean NDVI. The water year of the fire was excluded from analysis because mean annual NDVI could include both burned and unburned conditions. We characterized fire severity using the one-year post-fire classification rather than the immediate post-fire classification to better capture fire effects on vegetation including delayed mortality (Miller & Thode, 2007). Each burned polygon was additionally attributed with an area-weighted estimate of basal-area and canopy-cover change from Miller et al. (2009).

The magnitude and trend of ET change was estimated for fire and forest treatment areas using the regression equation in Figure 2. To account for post-fire interannual variability, we used the following equation:

$$\Delta ET = (ET_{postfire\_burned} - ET_{postfire\_unburned}) - (ET_{prefire\_burned} - ET_{prefire\_unburned})$$

where ET in unburned areas was determined as the mean of all unburned polygons in the watershed within 250 m in elevation of the target burned polygon. In this way, ET change was calculated for each water year and then averaged for subsequent analysis. In order to estimate post-impact ET, we subtracted ET change determined using the above equation from a 5-year average of pre-disturbance ET. Finally, we estimated the cumulative ET reduction for fires where ΔET recovered to a zero or positive value or to the end of the available record (water year 2016) if fires were recent. Change in ET for all burned areas was averaged each year to calculate the influence of forest fire on basin-wide ET with respect to mean annual runoff.

3. Results

3.1. Forest Treatments

Two intensively thinned compartments at Blodgett Forest (basal-area reductions of 68 and 45%) showed NDVI changes that were readily evident (Figure 3a); however, the statistical significance of these changes could not be evaluated due to the small sample size. Moderate thinning (change in basal area = 27%) at Blodgett

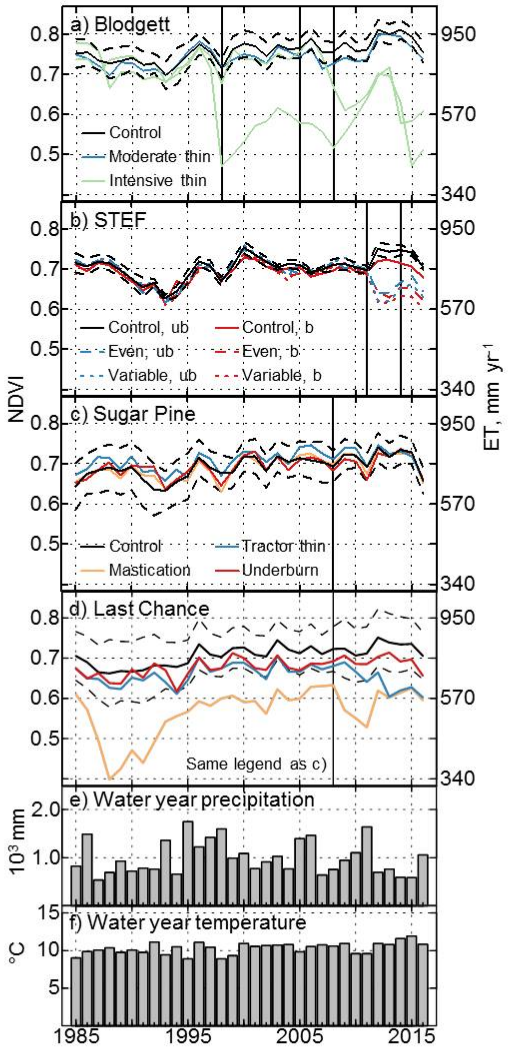

Figure 3. NDVI change for forest treatments shown by vertical lines. a) Blodgett Experimental Forest, where vertical lines from the left indicate intensive thinning in 1998, moderate thinning 2004-2006, and intensive thinning in 2008, b) Stanislaus-Tuolumne Experimental Forest (STEF), where vertical lines from the left indicate initial thinning in 2011 followed by underburns in half of the units in 2014, b=burned and ub=unburned, c) SNAMP Sugar Pine site and d) SNAMP Last Chance site, where the vertical line indicates initial year of treatments in 2008. Dashed lines indicate standard deviation around the control blocks. Panels e) and f) show mean annual precipitation and temperature for the central Sierra Nevada area. Note that tick labels for ET are based on Figure 2, and thus the axes are non-linear. See Table S1 for information on treatments.

resulted in an NDVI change that barely exceeded the standard deviation of control plots and was non-significant at the alpha = 0.05 level (Table S1).

The highly productive STEF sites exhibited a large and statistically significant change in NDVI accompanying basal-area reductions of 41-46% across all treatments, except on those plots treated with only an underburn (Figures 1b and 3b). Control plots with an underburn treatment changed less than did control plots that received no treatment, associated with a change in basal area of +5% for control-only versus +0.6% for control-plus-underburn plots. It should also be noted that all STEF plots exhibited a drop in NDVI that was similar in magnitude to that observed in the treatment plots during an extended period of lower-than-average precipitation in the late 1980’s and early 1990’s.

Among the SNAMP treatment areas, only tractor-thin treatments at Last Chance (a decrease in basal area of 9%) exhibited a significant NDVI change between 2008 and 2013 (Figure 3c, d). Despite larger basal area decreases at Sugar Pine (11 and 15%, respectively), there were no apparent changes in NDVI. There was no change in NDVI associated with controlled burns. Mastication treatments at Last Chance may have occurred as early as 2008 as seen in Figure 3d, though by 2013 no significant change is evident. Most areas exhibited pronounced NDVI change in 2015 and 2016, in association with much lower than average precipitation and higher temperatures (Figure 3e, f).

3.2. Forest Fire

Figure 4a depicts a typical forest-fire NDVI time series and Figure 4b shows change in NDVI distribution before the fire and during recovery for both burned and adjacent unburned areas. Areas with a burn severity classified as low or none changed little; some of these areas were bare rock and soil and the low severity reflected a low initial vegetation density. Similarly, the broader NDVI distribution and smaller median value of unburned versus pre-fire areas (Figure 4b) indicates more heterogeneous and lower forest densities in areas that did not burn. The overall change in NDVI of approximately 0.13 units in the year following fire corresponded with a change in basal area of 51% over the area of the Choke fire (Table S2). Decreased NDVI persisted for over 10 years across much of the fire area. As with the forest-treatment data, substantial drought effects were apparent in 2015-2016.

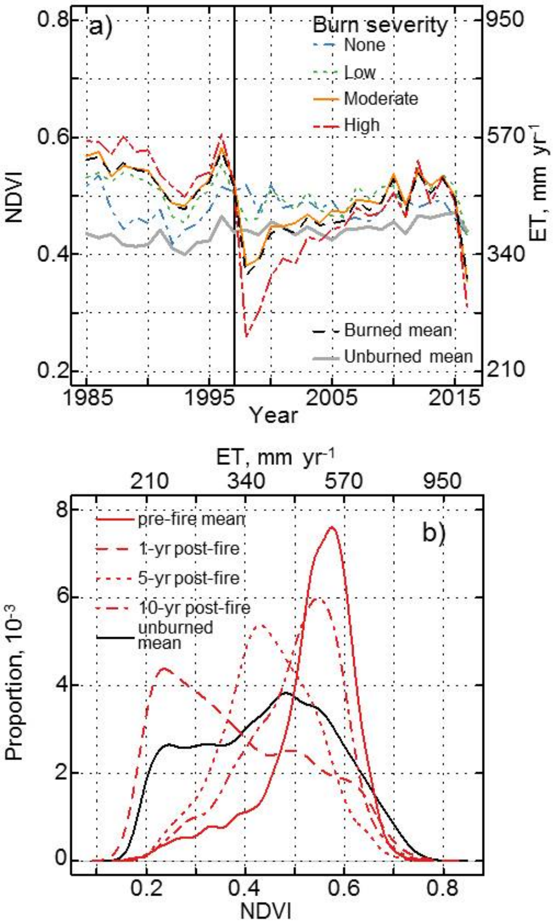

Figure 4. a) NDVI progression for the area of the 1997 Choke Fire in the Kings River watershed. The unburned mean was derived from randomly selected 90-m square polygons within the same elevation range as the Choke Fire and outside of all areas burned during the 1990-2008 period. Year of the fire is marked by a vertical black line. b) NDVI distribution within the Choke Fire perimeter before the fire, 1, 5, and 10 years post burn, and the mean of unburned areas (black line) for the 10 years post-burn (1998-2007). Note that tick labels for ET are based on Figure 2, and thus the axes are non-linear. See Tables S2 and S3 for information on fires.

Figure 5 illustrates NDVI and ET elevational variability in burned and unburned areas during 1990-2008. Burned area NDVI was broken into mean NDVI five years prior to fire, one year post fire, and mean NDVI over five years following fire for all fires that occurred in each elevation band. Pre-fire NDVI followed a similar elevation trend to unburned areas, though it was substantially higher than unburned areas below 500 m in the American. Fire decreased one-year post-fire NDVI means by 0.2 units or more at elevations below 2000 m. The shift was less dramatic at higher elevations in the Kings. There were no large fires above 2000 m in the American between 1990-2008. NDVI recovery was greatest below 2000 m in the Kings and below 1000 m in the American.

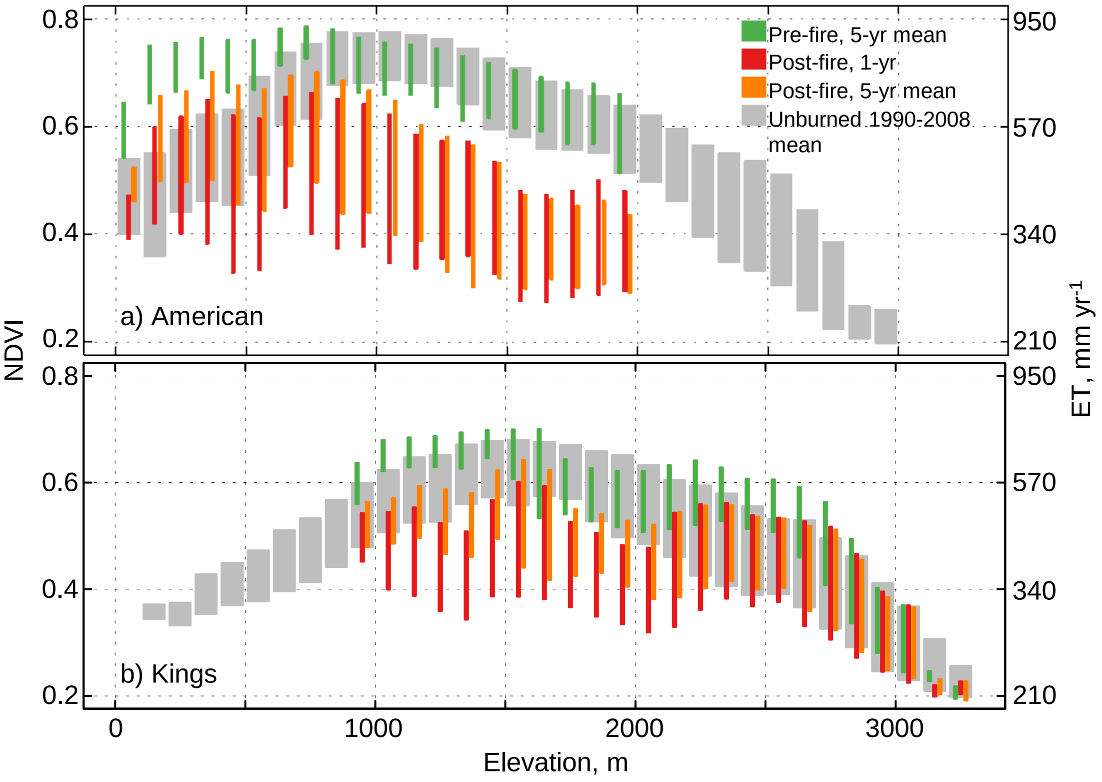

Figure 5. NDVI and ET change due to fire by 100-m elevation band for all fires greater than 100 ha 1990-2008 in the American (a) and Kings (b) watersheds. Bars span the 25th to 75th percentiles. Green bars indicate the NDVI mean (control) over the 5 years prior to the fire. Grey shaded area indicates the mean 25-75 percentile of NDVI values for the entire watershed that did not burn during this period.

Estimated ET change due to fire was substantial in both watersheds. Pre-fire annual ET values averaged 680 mm and 510 mm between 1000-2000 m elevation in the American and Kings, respectively (Figure 6a). ET peaked at around 660 mm at 1400 to 1500 m elevation in the Kings and declined to about 440 mm at 2700 m (18 mm per 100 m elevation change) and then dropped below 300 mm at 2900 m and above. This pattern corresponds to energy limitation and thus lower vegetation density at higher elevations (Goulden & Bales, 2014). Pre-fire annual ET peaked close to 830 mm in the 950-m elevation band of the American and declined to near 560 mm at 2150 m (22 mm per 100 m elevation change). No fires over 100 ha occurred above 2000 m elevation in the American during the study period despite a large area.

ET reduction at a given elevation due to fire was greater per unit reduction in basal area in the American than the Kings (Figure 6a, c) and persisted for longer periods in the American than in the Kings (Figure 6b, d). High basal-area

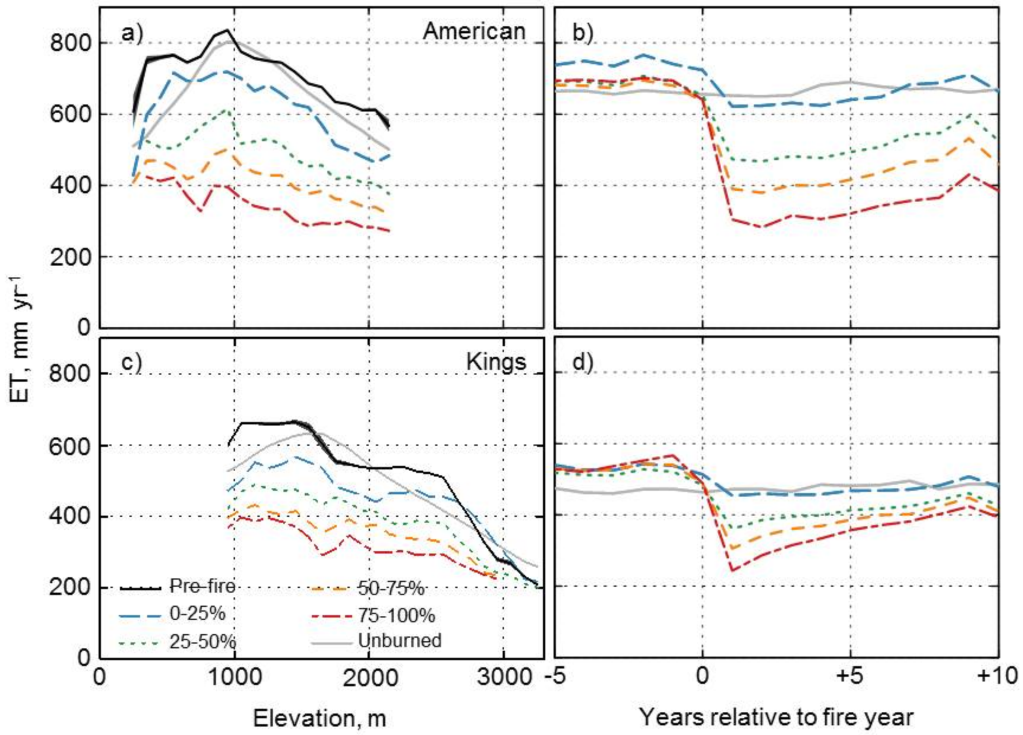

Figure 6. Impact of basal area reduction by forest fire on estimated evapotranspiration change, as determined by the mean 5-year change in ET difference between burned and unburned areas before and after the fire. Left panels (a, c) depict variation by 100-m elevation band. Only elevations with fires in the 1985-2013 period are shown. The black line is the estimated pre-fire 5-year mean ET. Right panels (b, d) illustrate the variation temporally from 5 years prior to 10 years after the fire. Shaded areas indicate plus and minus the standard error where greater than the thickness of lines (about 10 mm yr^{-1}). Data for these plots are summarized in Tables S2 and S3.

reduction (75-100%), which corresponds to high-severity fire, resulted in a decrease in ET of 320-440 mm yr^{-1} in the 1000-2000 m elevation range of the American compared to 200-310 mm yr^{-1} in the Kings. This difference was substantially less for a 25-50% basal-area reduction (190-260 mm yr^{-1} versus 100-190 mm yr^{-1}). Differences were smaller when compared to unburned areas of the watershed. Overall, the mean 5-year post-fire ET reduction was 265 mm in the American and 113 mm in the Kings. Recovery following fire took about nine years for 0-25% basal-area reduction in the American versus three years for the Kings. Areas experiencing 75-100% basal-area reduction recovered at 17 and 9 mm yr^{-1} in the Kings and American basins, respectively (average recovery time was approximately 14 years in both watersheds).

Net ET reduction from all timber fires during 1990-2008 in the American was about double that in the Kings (210 vs. 100 mm ha^{-1}). The maximum estimated net ET reduction was 65 million m^3 yr^{-1} across the entire American basin versus 14 million m^3 yr^{-1} for the Kings (Figure 7). It is important to note that these values peak in 2009, the year after the last fire in the analysis, and would continue to climb if subsequent fires were included.

4. Discussion

4.1. Using NDVI to Quantify the Effects of Disturbance on ET

Drought conditions shifted the NDVI-ET relationship (Figure 2) somewhat as identified previously (Goulden et al., 2012), whereas shifts due to disturbances such as fire and management (thinning) are less apparent. Measurements

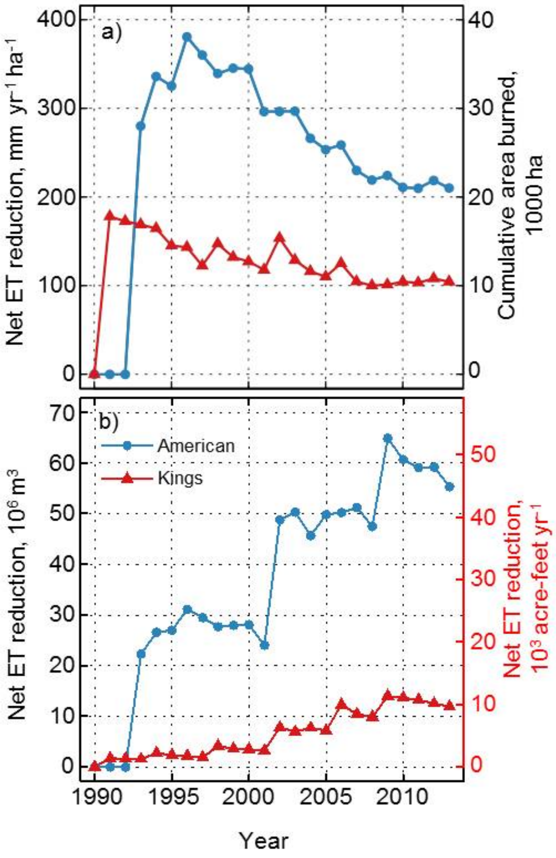

Figure 7. a) Net annual ET reduction depth per unit area burned (bold lines) and cumulative area burned (dashed lines), and b) net annual ET reduction volume resulting from fires in the American and Kings River watersheds 1990-2008. Note the only fires through 2008 were included in the analysis.

associated with drought, and the combination of fire/drought and management/drought, plot slightly lower than the overall regression line yielding a smaller change in ET per unit change in NDVI. Points associated with just fire or just management exhibit a similar relation to the non-drought trend, though more observations are needed to fully explore this issue. In summary, the fundamental relation used in this study appears to be robust to changes wrought by forest disturbance, especially considering that half of the observations (39 of 78) used in construction of the regression were affected by drought or forest disturbance.

4.2. Key Controls on ET Decline and Associated Uncertainties

The full impact of fire or mechanical disturbance on evapotranspiration may be estimated by the following heuristic equation:

Cumulative ET reduction = Area treated × Initial ET change × Effective duration of the change

Figures 3 and 4 indicate that beyond a certain threshold of thinning, the duration of NDVI change is likely to be the most-sensitive parameter for estimating integrated change in ET. Area is generally known to within a few percent and the initial change should be easy to estimate if the treatment date is known. Subsequent forest recovery and evolution of NDVI depends on follow-up treatments, intensity of the initial treatment, ensuing meteorology, forest type, and other factors such as insect outbreaks causing tree mortality. NDVI recovered nearly 50% of its original value within 3-4 years of the Choke fire (Figure 4), though full recovery took approximately 10 years. Hence, the effective duration of the initial change was five years or half the time to full recovery. Assessments of the impact of forest change as in Figure 7 could contribute to future planning of watershed restoration projects with relevance to designing treatments and justifying funding.

Central to the utility of methods introduced here is the assumption that forest disturbance and resulting changes in NDVI translate to changes in ET of similar relative magnitude to those observed at flux tower sites. Ongoing observations and drought-induced forest mortality at these and other sites suggest that this is the case (Figure 2; Bales et al., 2018). Future analyses should consider effects of drought, which tend to reduce ET for a given NDVI level. Moreover, the regression in Figure 2 underestimates ET in higher-productivity forests, which tend also to be the areas of highest management concern due to over stocking and fire risk, as well as species recovery. These middle-elevation mixed-conifer forests are also where forest thinning may have the greatest impact on ET (e.g. Figure 6). Changes in the ET-NDVI relation due to forest fire and forest management will require further experimental data, particularly as forest densities recover to pre-suppression-era densities, with fewer and larger trees.

A limitation to this work was the lack of readily available high-quality forest-treatment data that span the range of forest types, treatments, and/or climate zones of the Sierra Nevada. The four data sets obtained for this study demonstrate the potential for relating remote sensing of vegetation indices with accurate assessments of forest density, as well as the potential to scale these observations to full watersheds. The U.S. Forest Service Activity Tracking System (FACTS) database provides a promising starting point, though additional work will be required to obtain exact treatment dates as well as pre- and post-treatment forest-density metrics. Data for forest fires are much more complete and available, providing a solid basis for future analyses of this type. Indeed, given that approximately 75% of the forested landscape in the Sierra Nevada may be treated only by fire (North et al., 2015), it will be critical to estimate the further effects of more-extensive managed fire on evapotranspiration.

4.3. Patterns of ET Decline with Fire and Management

Changes in NDVI and thus ET of Sierra conifer forests following thinning or fire were observed to be consistent with changes in forest density indicated by basal area and canopy cover. Among forest treatments, the smallest detected change in NDVI was -0.088 units in the STEF evenly thinned unburned treatment areas (Table S1). Tractor thinning at Last Chance yielded an NDVI change of -0.102 units, but thinning of a similar or larger magnitude at Sugar Pine yielded no significant NDVI change (Table S1), likely the result of canopy retention greater than 60%, in adherence with the Pacific-fisher conservation strategy (Fry et al., 2015). Mastication treatments at Last Chance may have produced significant changes in NDVI assuming they occurred in 2008 (Figure 3d). However, information about the timing of those treatments was lacking and by 2013 there was no longer a significant difference from prior to 2008.

The duration of NDVI change following treatment lasted longer for both more-intensively thinned areas (Blodgett) as well as those treatments that were subsequently burned after thinning (STEF). While measured basal area and canopy cover appeared to be correlated with annual mean NDVI for the year of measurement in treated and control areas, the additional data and analyses required to elucidate these relations were beyond the scope of the study. More detailed information is needed about treatments (e.g. thin from below or above, canopy retention or removal, etc.) to more-rigorously explore relationships between treatment characteristics and ET change.

The magnitude and duration of NDVI change due to forest fire varied substantially by elevation and watershed, with a maximum change at 1000-2000 m elevation (Figure 5). Unburned conifer forests in the American and Kings watersheds exhibited peak NDVI at 1050 m (0.71 ± 0.09) and 1650 m (0.61 ± 0.09), respectively. Pre-fire NDVI tracked the unburned-forest elevation trend in each watershed, while post-fire NDVI below 2000 m dropped approximately 0.1-0.2 units below that of unburned forests after one year. Mean NDVI recovery over 5 years post fire was 0.06 units in both watersheds. NDVI change following fire was minimal above 2700 m in the Kings, though the sample size was small, and no fires occurred above 2000 m in the American during the study period.

Burned areas in the American River watershed exhibited a greater reduction in estimated ET per proportional reduction in basal area than in the Kings, a result primarily due to initially higher basal area in the American (Figure 6a, c). At 1000 m in the American, annual ET decreased 320 mm with a 50% decrease in basal area, compared to 200 mm in the Kings. This difference between watersheds was roughly consistent between 1000 and 2000 m elevation. Differences between pre- and post-fire 5-year ET remained roughly consistent for the entire range of elevations burned during the study period in the American. Given little energy limitation (Goulden and Bales, 2014), ET decline from 1000 to 2000 m must be driven primarily by decreasing forest density. Post fire, however, there may also be a contribution due to faster recovery rates at lower elevation offsetting greater initial decreases in ET following disturbance. In contrast, small differences between pre- and post-fire ET above 2700 m in the Kings indicate increasing energy limitation and low vegetation density.

Most ET reduction in the American was driven by large 7000-8000 ha fires in 1992 (Cleveland), 2001 (Gap, Ponderosa, and Star), and 2008 (Government) (Tables S2 and S3). All of these fires except the Government Fire contained large areas of high-severity burn, and over half of the fire area during 1990-2008 burned at high severity (compared to only 9% in the Kings watershed). In general, this is undesirable for ecological as well as human health and safety reasons. If the high-severity burn areas (>75% reduction in basal area) had instead burned at moderate severity (25-75% reduction), ET reduction would have been 80% of the high-severity change. Hence, even with a reduction in fire severity there would remain a substantial impact to ET rates.

4.4. Impact of Reduced Fire Frequency on Water Availability

Tracking overall changes in basin-wide ET due to forest fire revealed interesting temporal trends. ET reduction in the American basin was approximately double that of the Kings after 2008, consistent with the 5-year post-fire estimates (Figure 7a). Coupling this with the fact that 80% more area burned in the American compared to the Kings (36,824 vs. 19,088 ha), net ET reduction due to fires between 1990-2008 peaked in the American at over four times that of the Kings (Figure 7b; 65 vs. 14 million m^3 yr^{-1}). Given that only 11 and 9% of conifer forest area burned in the American and Kings watersheds, respectively, one could anticipate much greater ET reduction if fires burned more closely to the expected fire-return interval for forested areas, because the average severity of modern fires investigated here was moderate approximating historic forest densities (Collins et al., 2011).

An outstanding applied research question involves quantifying net ET impact of returning forests to densities that existed prior to the era of fire exclusion. We make an initial estimate by extrapolating results from this analysis with the caveat that there are substantial limitations to this approach and further work is needed. Almost all of the American River forests have a historical mean fire return interval of less than 20 years (Safford & Van de Water, 2013), which is far more frequent than the current interval of 85 years. Hence, during the 1990-2008 period, all forests would have burned historically, potentially resulting in nearly 10 times the net annual ET reduction, or 650 million m^3 yr^{-1}. This amount is greater than 10% of the mean annual unimpaired runoff from the basin during the 1992 and 1994 drought years, and on average 5.4% for the 1990-2008 period (California Department of Water Resources, 2016). In contrast, only 43% of forests in the Kings have mean historic fire return intervals of less than 20 years, which is five times what burned in 1990-2008, and had this area burned it could have resulted in an ET reduction of 4.5% of the unimpaired runoff.

4.5. Next Steps

Research questions stimulated by this initial investigation may be grouped into three areas. First, there is a need to further evaluate factors affecting the relation between NDVI or remotely sensed indices and ET at measurement locations. This may include examining the impact of seasonal and inter-annual temperature and precipitation patterns on the correlation, as well as the sensitivity of the correlation to changes in forest density or thinning characteristics. Second, we require better estimates of recovery rate and how this varies by treatment type and intensity as well as elevation, latitude, and climate in order to scale measures of forest density with observed NDVI across the region. Third, there exists the potential to predict forest response to treatments and disturbance, particularly in areas where there has been a fundamental shift in vegetation type due to disturbance and climate change. Potential areas of investigation include estimating ET and CO_2 flux variation during forest succession following disturbance and, using space-for-time substitution, predicting forest trajectories under different climate regimes with associated management implications.

5. Conclusions

There are many potential benefits to reducing the forest overstocking that has occurred with fire exclusion, including the potential ET reductions explored in this paper. Here, we have identified that for NDVI values around 0.7, changes of 0.2-0.3 units can occur in high-fire-severity burn areas, corresponding to declines in ET from 800 to 280-450 mm yr^{-1}. The potential ET change peaks in middle elevations around 1000-2000 m. Estimated ET reductions due to forest treatment ranged from 153 mm at the minimum detection limit for NDVI change (0.09 units) to over 300 mm in the intensive thinning units in the Blodgett Forest. Intensive thinning in Blodgett and the Stanislaus-Tuolumne Experimental Forests was similar in magnitude to moderate- and high-severity fire, particularly in the American River basin. Returning fire to areas that once burned frequently has the potential to reduce forest ET by approximately 5% of full natural outflows from the American and Kings River watersheds.

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Table S1. Summary forest treatment data

Name Latitude / Longitude	Treatment type (number of units)	Year of treatment	Basal area, m^2 ha^{-1} ± std. dev.		Canopy cover, %		NDVI change[1]	ET change, mm yr^{-1}
			before	after	before	after		
Last Chance[2]	Control (294)	NA	39.8 ± 16.9	42.1 ± 17.3	60.7 ± 16.8	56.8 ± 17.5	**+0.034**	+74
	Mastication (19)	2008-2013	28.3 ± 8.5	26.2 ± 7.1	45.5 ± 7.9	37.3 ± 7.8	-0.023	-54
39° 05’ 25”	Tractor thin (6)	2008-2013	33.6 ± 5.5	30.5 ± 4.4	49.9 ± 3.0	39.1 ±3.8	**-0.102**	-186
-120° 34’ 49”	Underburn (2)	2008-2013	34.3	34.3	59.9	54.8	+0.001	-6
Blodgett[3]	Control (6) (before: 2001-2004) (after: 2014)	NA	73.8 ± 9.6	81.14 ± 9.8	77.2 ± 5.1	74.9 ± 3.5	+0.029	+66
38° 53’ 45”	Moderate thin (6)	2005-2011	49.1 ± 4.0	35.9 ± 2.3	68.6 ± 3.6	58.6 ± 3.4	-0.006	+2
-120° 39’ 16”	Intensive thin (1)	1998	58.9	19.1	-	29.1	-0.185	-310
	Intensive thin (1)	2008	44.1	24.3	69.1	45.1	-0.112	-218
STEF[4]	Control, unburned (4)	NA	63.8 ± 8.6	67.0 ± 9.1		65.1 ± 4.0	**+0.037**	+67
	Even thin, unburned (4)	2011	65.0 ± 11.8	35.9 ± 6.6		40.5 ± 2.5	**-0.088**	-153
38° 10’ 34”	Variable thin, unburned (4)	2011	71.3 ± 6.2	38.4 ± 4.0		35.0 ± 2.2	**-0.109**	-195
-119° 59’ 45”	Control, burned (4)	2014	67.2 ± 10.8	67.6 ± 15.4			-0.021	-41
	Even thin, burned (4)	2011, 2014	70.5 ± 12.3	40.8 ± 9.5			**-0.096**	-164
	Variable thin, burned (4)	2011, 2014	67.2 ± 10.6	39.4 ± 11.9			**-0.118**	-201
Sugar Pine[2]	Control (182)	NA	71.4 ± 33.0	65.4 ± 34.1	73.7 ± 13.5	71.5 ± 14.0	+0.005	+10
	Mastication (11)	2008-2013	60.8 ± 9.6	54.2 ± 10.2	77.2 ± 3.7	74.3 ± 4.2	-0.007	-13
37° 27’ 06”	Tractor thin (15)	2008-2013	63.9 ± 17.5	54.6 ± 16.2	75.6 ± 5.7	71.3 ± 6.3	-0.024	-46
-119° 37’ 41”	Underburn (4)	2008-2013	64.9 ± 23.0	59.3 ± 23.1	76.9 ± 4.8	74.5 ± 5.6	+0.002	+3

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[1] In treatment units, this is relative to the change in the control: $(\mu_{tb} - \mu_{ta}) - (\mu_{ca} - \mu_{cb})$ where μ is the mean NDVI value for either 5 years before or 4-5 years after treatment in treated and control units, *t* indicates treated, *c* indicates untreated, *a* is after treatment, and *b* is before treatment. For control units, the value indicates difference in control units before and after treatments only. Bold type indicates a significant difference at p=0.05 or less using a 2-way ANOVA with significance determined by interaction between treatment and before and after designation. Statistical significance for change in controls used a pair-wise t-test.

[2] Last Chance and Sugar Pine treatments took place between 2008 and 2013. Pre-treatment NDVI was taken as an average of 2004 to 2008 annual NDVI values. Post-treatment NDVI was taken as an average of 2013-2016 annual values (P. Saksa, pers. comm., 2017).

[3] Blodgett control and moderate-thin compartments were evaluated for mean annual NDVI for 2000-2004 and 2012-2016. Control and intensive-thin sites were evaluated for 1993-1997 (before) and 1999-2003 (after) for the site treated in 1998 and for 2003-2007 (before) and 2009-2013 (after) for the site treated in 2008 (A. Thompson, pers. comm., 2017).

[4] STEF treatments were evaluated for NDVI change by averaging annual NDVI for the period 2006-2010 (before) and 2012-2016 (after) (E. Knapp, pers. comm., 2017).

Table S2. Kings River watershed fires 1990-2008

Fire	Year	Area, ha	Elevation range, m	Basal area reduction class, %	% Area by class	5-year post-fire mean ET change, mm	Years to recovery[1]
Avalanche	1990	1186	1790-3035	0-25	56.3	-92	13
				25-50	15.6	-176	21
				50-75	15.2	-222	23
				75-100	12.9	-257	23
Buck Peak	1993	880	1899-2842	0-25	64.1	-91	14
				25-50	18.7	-138	17
				50-75	13.2	-194	18
				75-100	4.1	-241	19
Choke	1997	1612	1905-3140	0-25	31	-22	6
				25-50	16.6	-94	13
				50-75	21.3	-161	16
				75-100	31.1	-248	17
Sugarloaf	1997	152	2192-2408	0-25	69.3	-42	8
				25-50	15.9	-72	11
				50-75	10.2	-96	12
				75-100	4.5	-164	11
Williams	1999	259	2443-2874	0-25	92.8	-48	10
				25-50	5.1	-137	16
				50-75	2.1	-113	17
				75-100	0	NA	NA
Millwood	2000	110	1107-1512	0-25	30.7	-44	5
				25-50	12.5	-183	15
				50-75	28.4	-247	15
				75-100	28.4	-245	15

Table S2. (cont.)

Fire	Year	Area, ha	Elevation range, m	Basal area reduction class, %	% Area by class	5-year post-fire mean ET change, mm	Years to recovery[1]
Burnt	2001	973	1698-3019	0-25	61.6	-49	8
				25-50	15.7	-105	11
				50-75	15.6	-144	13
				75-100	7.1	-189	14
Highway	2001	1719	932-1679	0-25	45.7	-103	11
				25-50	17.5	-196	14
				50-75	25.5	-249	15
				75-100	11.4	-291	15
Palisade	2002	637	2565-3297	0-25	37.9	-28	6
				25-50	29.1	-47	10
				50-75	17.4	-76	13
				75-100	15.6	-82	13
Williams	2003	1516	2303-2901	0-25	77.9	-80	11
				25-50	13.5	-121	12
				50-75	6.8	-145	12
				75-100	1.9	-169	13
Comb	2005	4222	1485-2904	0-25	48.7	-40	6
				25-50	20.1	-101	9
				50-75	20.9	-151	10
				75-100	10.3	-212	11
Burnt	2006	275	2147-2844	0-25	85.2	-57	7
				25-50	8.3	-94	9
				50-75	6.5	-124	10
				75-100	0	NA	NA

Table S2. (cont.)

Fire	Year	Area, ha	Elevation range, m	Basal area reduction class, %	% Area by class	5-year post-fire mean ET change, mm	Years to recovery[1]
Roaring Ridge	2006	753	1676-2749	0-25	97.3	-81	8
				25-50	2.3	-133	10
				50-75	0.4	-141	10
				75-100	0	NA	NA
Tehipite	2008	5020	1267-2850	0-25	70.8	-100	7
				25-50	13.3	-154	8
				50-75	11.6	-199	8
				75-100	4.2	-257	8

[1] Years to recovery was defined as the number of years post fire until mean annual NDVI equaled or exceeded the pre-fire 5-year mean.

Table S3. American River watershed forest fires 1990-2008.

Fire	Year	Area, ha	Elevation range, m	Basal area reduction class, %	% Area by class	5-year post-fire mean ET change, mm	Years to recovery[1]
Cleveland	1992	9338	1002-1876	0-25	14.7	-45	8
				25-50	10.9	-199	16
				50-75	18.2	-269	18
				75-100	56.1	-391	20
Kelsey	1994	514	574-771	0-25	22.1	-92	10
				25-50	12.3	-154	14
				50-75	24.3	-264	18
				75-100	41.3	-382	19
Mill	1995	51	1639-1721	0-25	2.9	-79	4
				25-50	2.9	-110	5
				50-75	41.2	-240	13
				75-100	52.9	-354	18
Gap	2001	1034	1538-1863	0-25	9.3	-37	6
				25-50	8.3	-157	13
				50-75	16.4	-255	15
				75-100	66	-306	15
Ponderosa	2001	1224	284-820	0-25	21.6	-122	11
				25-50	18.8	-217	13
				50-75	25.6	-301	14
				75-100	34	-400	15
Star	2001	6332	1089-2150	0-25	22.3	-126	11
				25-50	13.6	-208	14
				50-75	21.6	-276	14
				75-100	42.5	-401	15

Table S3. (cont.)

Fire	Year	Area, ha	Elevation range, m	Basal area reduction class, %	% Area by class	5-year post-fire mean ET change, mm	Years to recovery[1]
Hunter	2002	283	1599-1798	0-25	39.2	-150	12
				25-50	30.4	-272	13
				50-75	23.8	-348	14
				75-100	6.6	-400	14
Plum	2002	767	1254-1652	0-25	73.9	-89	9
				25-50	12.9	-273	13
				50-75	10.4	-395	14
				75-100	2.8	-537	14
Cod Fish	2003	355	782-1285	0-25	62.2	-137	10
				25-50	18.2	-274	12
				50-75	14.9	-335	13
				75-100	4.8	-471	13
Freds	2004	3194	1227-2128	0-25	6.9	-176	10
				25-50	8.5	-222	12
				50-75	19.8	-292	12
				75-100	64.8	-382	12
Stevens	2004	401	370-854	0-25	21.2	-132	11
				25-50	20	-225	12
				50-75	31.9	-314	12
				75-100	27	-431	12
Ralston	2006	3586	361-1411	0-25	60.7	-110	8
				25-50	15.3	-214	9
				50-75	16.5	-299	10
				75-100	7.6	-397	10

Table S3. (cont.)

Fire	Year	Area, ha	Elevation range, m	Basal area reduction class, %	% Area by class	5-year post-fire mean ET change, mm	Years to recovery[1]
Government	2008	8467	714-2046	0-25	38.6	-151	7
				25-50	17.9	-221	7
				50-75	21.2	-293	8
				75-100	22.3	-396	8
Peavine	2008	272	1342-1551	0-25	49.2	-155	6
				25-50	16.3	-264	8
				50-75	17.1	-370	8
				75-100	17.4	-476	8

[1] Years to recovery was defined as the number of years post fire until mean annual NDVI equaled or exceeded the pre-fire 5-year mean.