Title

Emerging Stress and Relative Resiliency of Giant Sequoia Groves Experiencing Multiyear Dry Periods in a Warming Climate

Journal

Journal of Geophysical Research Biogeosciences, 122(11)

ISSN

2169-8953

Authors

Su, Yanjun
Bales, Roger C
Ma, Qin
et al.

Publication Date

2017-11-01

DOI

10.1002/2017jg004005

Peer reviewed

Emerging stress and relative resiliency of Giant Sequoia groves experiencing multi-year dry periods in a warming climate

Yanjun Su[1,2], Roger C. Bales[2], Qin Ma[2], Koren Nydick[3], Ram L. Ray[2], Wenkai Li[4], Qinghua Guo[1,2*]

[1]State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China
[2]Sierra Nevada Research Institute and School of Engineering, University of California, Merced, California 95343, USA
[3]U.S. National Park Service, Sequoia & Kings Canyon National Parks, Three Rivers, CA 93271, USA
[4]Guangdong Provincial Key Laboratory of Urbanization and Geo-simulation, School of Geography and Planning, Sun Yat-sen University, Guangzhou 510275, China
*Corresponding author: Qinghua Guo (guo.qinghua@gmail.com)

Key Points:

- **Giant Sequoia groves show vulnerability to moisture stress, though not the mortality seen in other conifer species in the 2011-15 drought**
- **Significant increases in vegetation density in groves over the past 30 years has increased evapotranspiration by 10%, to about 800 mm yr^{-1}**
- **Unprecedented decline in vegetation wetness occurred during the very warm 2011-2015 drought, larger than declines in the background forest**

Abstract

The relative greenness and wetness of Giant Sequoia (*Sequoiadendron giganteum*, SEGI) groves and the surrounding Sierra Nevada, California forests were investigated using patterns in vegetation indices from Landsat imagery for the period 1985-2015. Vegetation greenness (normalized difference vegetation index) and thus forest biomass in groves increased by about 6% over that 30-year period, suggesting a 10% increase in evapotranspiration. No significant change in the surrounding non-grove forest was observed. In this period, local temperature measurements showed an increase of about 2.2 ºC. The wetness of groves (normalized difference wetness index) showed no overall long-term trend, but responded to changes in annual water-year precipitation and temperature. The long-term trends of grove greenness and wetness were elevation dependent, with the lower rain-snow transition elevation zone (1700 – 2100 m) marking a change from an increasing trend at lower elevations to a decreasing trend at higher elevations. The 2011-2015 drought brought an unprecedented drop in grove wetness, over five times the 1985-2010 standard deviation; and wetness in SEGI groves dropped 50% more than in non-grove areas. Overall, the wetness and greenness of SEGI groves showed a larger response to the warming climate and drought than non-grove areas. The influence of droughts on the wetness of SEGI groves reflected effects of both the multi-decadal increase in forest biomass and the effects of warmer drought-year temperatures on the evaporative demand of current grove vegetation, plus sufficient regolith water storage of rain and snowmelt to sustain that vegetation through seasonal and multi-year dry periods.

1 Introduction

Giant Sequoia (*Sequoiadendron giganteum*, SEGI) trees, the sole living species in the genus *Sequoiadendron*, are among the largest trees (both in height and volume) and the oldest living things on Earth [*Cook*, 1955]. Currently, the natural distribution of SEGI trees is restricted to around 70 groves on the western slopes of California's Sierra Nevada, and most SEGI groves are within Sequoia and Kings Canyon National Parks and Sequoia National Forest. The species has grown in the Sierra Nevada for 2.6 million years and individual SEGI trees can persist for over three thousand years [Douglass, 1925; Sillet et al., 2015]. They are a unique and significant natural heritage to the region, and even to the world [*York et al.*, 2013a].

Over the past million years, cold glacial periods have been dominant, with brief warmer interglacial periods [*Millar*, 1996; *Millar*, 2003]. Recent fossil SEGI pollen deposits showed that the current extent of SEGI groves may have been established during the early Holocene, 12,000 years ago [*Anderson et al.*, 1995]. Thus, current SEGI grove locations represent a reaction to transient ecological and climatic conditions specific to the past few thousands of years [*Anderson et al.*, 1995]. During the past three decades, the Sierra Nevada has experienced both multi-year dry periods that characterize the past millennium, and unprecedented rising temperature that drives more-extreme droughts to which SEGI trees may be vulnerable [*Swetnam,* 1993]. Yet how the SEGI groves will respond to the changing climate and warmer droughts is still not well established [*Stephenson,* 1996; *York et al.,* 2013a]

Temperature is an important limitation to forest growth in the Sierra Nevada, especially at higher elevations [*Das et al.,* 2013; *Goulden and Bales,* 2014; *Trujillo et al.,* 2012]. A warmer temperature can extend the growing season and thus enhance SEGI growth; however, wildfire frequency within SEGI groves is also higher as temperature warms [*Mutch,* 1994]. Gaps created by wildfires are beneficial to the SEGI recruitment [*Meyer and Safford,* 2011; *van Mantgem et al.,* 2016; *York et al.,* 2006; *York et al.,* 2010; *York et al.,* 2015; *York et al.,* 2013b]. It is suggested that a minimum of ~0.1 ha gap is required for significant SEGI recruitment [*Stephenson*, 1994]. By contrast, consecutive dry periods may bring moisture stress to SEGI groves [*Hughes and Brown,* 1992]. SEGI growth, seeding, and recruitment are sensitive to grove moisture conditions [*Ambrose et al.,* 2015; *Harvey et al.,* 1980; *Kitzmiller and Lunak,* 2012; *Mutch,* 1994; *Wittstock et al.,* 2012]. Dry periods during the last three decades (e.g. 1987-1992 and 2011-2015) resulted in significantly reduced water availability. It was estimated that over 30% of the forests in California experienced measureable loss in canopy water content from 2012 to 2015, with about 10% of these forests experiencing severe loss (>30%) in canopy water content (*Asner et al.,* 2016).

There are also projections that increasing temperature during dry periods will intensify drought effects [*Diffenbaugh et al.,* 2015; *Williams et al.,* 2015]. The Sierra Nevada has a montane Mediterranean climate [*Mooney,* 1977], with over 90% of annual precipitation falling in the local winter and spring [*Goulden and Bales,* 2014]. Rain and snowmelt stored in the regolith provide the major water source for the southern Sierra Nevada forests during long and dry summers [*Bales et al.*, 2011]. The increasing temperature induces earlier snowmelt, and can prolong the summer dry periods [*Westerling et al.*, 2006]. This rising-temperature effect will become stronger in high elevations where most precipitation currently falls as snow [*Kirchner et al., 2014*; *Trujillo et al.,* 2012].

The aim of this study was to assess the relative vulnerability of SEGI groves to a warming climate and multi-year dry periods. Three questions were addressed. First, how have forest vegetation density, moisture stress and forest water balance changed over the past three decades? Second, are groves more or less responsive to drought than is the surrounding forest? Third, which grove areas may be vulnerable to multi-year dry periods?

2 Materials and Methods

We evaluated the overall wetness and greenness trends of SEGI groves and adjacent non-grove forest from 1985 to 2015, analyzed the factors influencing the trends, and examined the influence of multi-year dry periods on groves. Wetness was represented by the normalized differenced water index (NDWI), which is a good proxy for plant water stress [*Gao,* 1996; *Jackson et al.,* 2004]; while greenness was represented by the normalized difference vegetation index (NDVI), which is highly correlated to plant health, biomass, and evapotranspiration [*Carlson et al.,* 1995; *Goulden et al.*, 2012; *Su et al.,* 2016b; *Zheng et al.,* 2004]. NDWI and NDVI were developed from Landsat images, which have been widely used to monitor vegetation conditions [*Gao,* 1996; *Gu et al.*, 2008]. Linear regression was used to examine the temporal trends of the vegetation indices and climate attributes. The coefficient of determination (R^2) and correlation coefficient (R) were derived from each regression, and the test statistic was used to evaluate their significance.

2.1 Study area

The study domain covers 70 SEGI groves and comparable non-grove areas (Figure 1). The groves occupy about 150 km^2, with the six largest ones accounting for half of this area (Table S1). The groves range in size from about 0.003 km^2 to

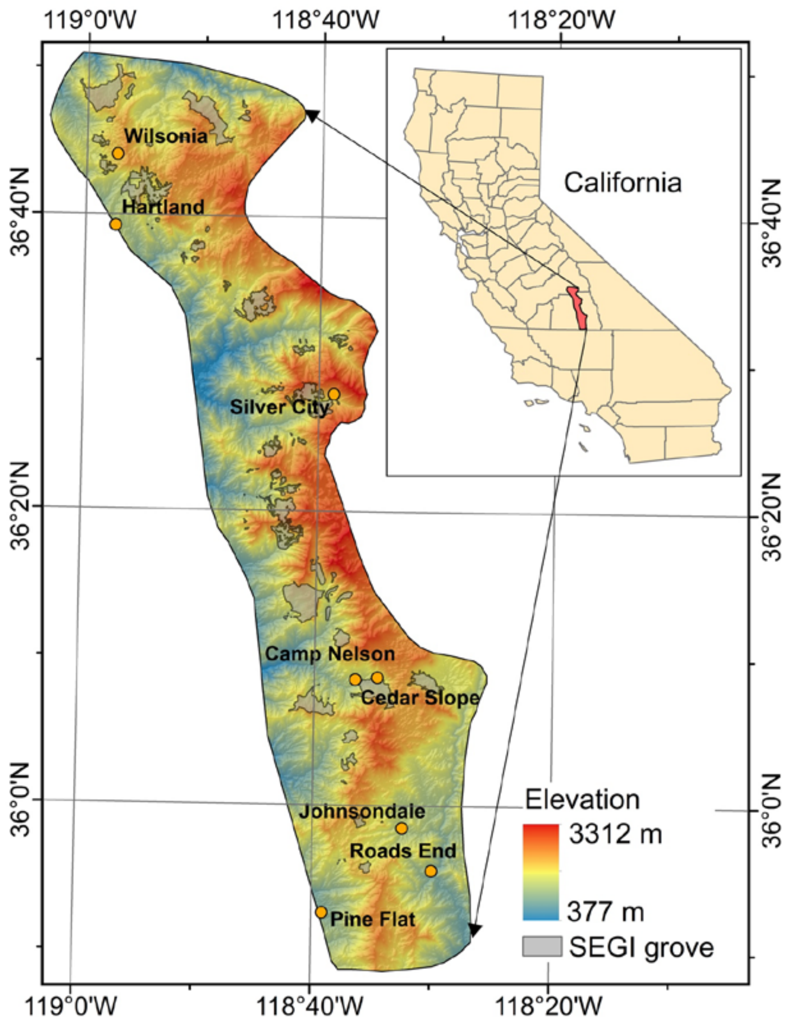

Figure 1. Location and elevation of the SEGI groves and the study domain. The SEGI grove boundaries within the study domain were provided by the Sequoia & Kings Canyon National Parks, and were developed from field survey.

over 15 km^2, with an average of 2 km^2. They range in elevation from 1100 m to as high as 2750 m, with most concentrated in the 1800-2100 m range (Figure S1a). The background forest at 1100 m is pine-oak, with a ponderosa pine (*P. ponderosa*) and oak overstory (mainly *Q. chrysolepsis*). The higher elevations grade to a Sierran mixed-conifer forest with interspersed patches of montane shrubland, where the upper canopy is mostly white fir (*A. concolor*), ponderosa pine, black oak (*Q. kelloggii*), sugar pine (*P. lambertiana*), and incense-cedar (*C. decurrens*).

2.2 Satellite imagery

Landsat surface-reflectance products from three sensors (Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI) were used to monitor the domain between 1985 and 2015 (Table S2). These surface-reflectance data are high-level products that have been through atmospheric correction using the Satellite Signal in the Solar Spectrum Radiative Transfer model [*Masek et al.*, 2013]. All available images during the local growing season (May 1 to September 30) were collected for each year from the corresponding Landsat sensor using the Google Earth Engine. A maximum-value composite (MVC) was calculated from the images in each year. MVC method examined the time-series images pixel by pixel, and retained the land-surface reflectance values with the highest NDVI for each pixel location. The MVC has been demonstrated to be highly correlated to green vegetation changes [*Delbart et al.*, 2006; *Holben*, 1986] and is capable of minimizing the common problems of single-date imagery (e.g., cloud contamination and atmospheric attenuation) [*Su et al.*, 2015; *van Leeuwen et al.*, 1999]. Note that all pixels with cloud coverage were excluded in the MVC generation process to ensure the quality of the resulting images. Two vegetation indices, NDWI and NDVI, were calculated from these time-series MVC images:

$$\mathrm{NDWI} = \frac{r_{\mathrm{NIR}} - r_{\mathrm{SWIR}}}{r_{\mathrm{NIR}} + r_{\mathrm{SWIR}}} \qquad (1)$$

where r_{NIR}, r_{SWIR}, and r_{R} are the land-surface reflectance of near infrared, short-wave infrared, and red band, respectively. The average NDWI and NDVI values of the 70 groves during the last three decades were 0.25-0.55 and 0.65-0.80, respectively (Figures S1c and S1d; Table S1).

Studies have shown that the three Landsat sensors can have around 5% differences in the surface reflectance data, and these differences can be significant in the resulting NDWI and NDVI [*Claverie et al.*, 2015; *Li et al.*, 2013]. In this study, we used the regression-based method proposed by Sulla-Menashe et al. (2016) to homogenize the NDWI and NDVI derived from the three sensors. A total of 50 1×1 km reference sites was randomly selected within the SEGI domain (Figure S2). Areas with black stripes in the ETM+ data were avoided in the selection procedure. The average NDWI and NDVI for each reference site were then calculated from the MVC composites of different sensors in the same year, and linear regression equations were built among these average NDWI/NDVI pairs. These regression equations were finally used to homogenize the NDWI/NDVI data from different sensors. In this study, we used the 2011 TM and ETM+ data and 2013 ETM+ and OLI data to build the homogenization equations. The R^2 of the regression equations among NDWI/NDVI from different sensors were all higher than 0.94 (Figure S3). The homogenization process was performed on the basis of TM data, and the 2012 ETM+ data and 2013-2015 OLI data were all calibrated to TM data.

$$\mathrm{NDVI} = \frac{r_{\mathrm{NIR}} - r_{\mathrm{R}}}{r_{\mathrm{NIR}} + r_{\mathrm{R}}} \qquad (2)$$

NDWI and NDVI values of all selected time-invariant objects from each year were averaged, and regression analysis was used to verify that there were no temporal trends in the data (Figure S4).

To further examine the consistency of the final time-series NDWI and NDVI products across the three sensors, we randomly chose five time-invariant objects (e.g., water bodies and bare rocks) within the SEGI domain. Each object had to be larger than two 30 × 30 m pixels. Then, the

2.3 Climate data

To assess the response of vegetation to the temporal climate patterns we computed the mean temperature and total precipitation for each water year (October 1 to September 30) from the gridded monthly data. For this analysis we used the 4-km monthly Parameter-elevation Relationships on Independent Slopes Model (PRISM) average-temperature and total-precipitation products. PRISM is an interpolated climate product based on nearly 13,000 precipitation stations and 10,000 temperature stations in the continental United States, and uses elevation as the main covariable [*Daly et al.*, 2008].

2.4 Auxiliary data

For elevation we used the global digital elevation model (DEM) developed from Shuttle Radar Topography Mission (SRTM) data, available in 1 arc second (approximately 30 m) resolution [*Farr et al.*, 2007]. The topographic wetness index (TWI) was calculated from the SRTM DEM:

$$\mathrm{TWI} = \ln \frac{a}{\tan b} \qquad (3)$$

where a is the upstream contribution area, and b is the local slope in radians. As seen from Eq. 3, TWI is a function of both slope and the upstream contributing area per unit width orthogonal to the flow direction, and is an index of surface-topographic control on hydrologic drainage [*Beven and Kirkby*, 1979]. The average TWI for the 70 groves ranged from 6.5 to 10.5, and around

70% of the groves have an average TWI around 8-9 (Figure S1b).

We used time-series Monitoring Trends in Burn Severity (MTBS) maps (1984-current) to identify burn severity and perimeters of fires [*Eidenshink et al.,* 2007]. MTBS classifies fires into five severity classes, i.e., increasing greenness, unburned to low, low, moderate, and high, based on analyst interpretation on Normalized Burn Ratio (NBR), delta NBR, relative delta NBR and high-resolution imagery. We used these data to identify wildfire influences on NDWI and NDVI patterns.

2.5 Trend analysis

We used regression analysis to detect trends in NDWI, NDVI, precipitation, and temperature. Data for SEGI grove points were averaged over all pixels within each grove polygon. To compare the overall trends in SEGI groves with background (non-grove areas within the study domain), we randomly sampled over 260,000 30 × 30 m pixels in background areas with the same elevation range as SEGI groves, which provided an equivalent number of non-grove pixels to grove pixels. The NDWI, NDVI, annual mean temperature, and annual total precipitation for each water year were extracted based on the geolocation of each randomly selected pixel. We applied the same regression analysis to these background data. We examined the correlations between vegetation indices (NDWI and NDVI) and climate attributes (temperature and precipitation) using regression analysis, including a lagging influence of one, two, and three years. Each data point here was the average NDWI or NDVI of all SEGI grove pixels of a certain water year versus the average annual temperature or precipitation of all SEGI grove pixels of the corresponding water year.

2.6 Factors influencing trends

We examined how the wetness and greenness of SEGI groves and background areas responded differently to different factors (i.e., elevation, TWI, average NDWI, and average NDVI). We divided each factor into a number of zones based on a constant interval (50 m for elevation, 0.5 for TWI, 0.05 for average NDWI, and 0.05 for average NDVI). Then, the SEGI grove pixels and background pixels were regrouped based on the divided zones of each factor. The changing trends of NDWI and NDVI with time in each zone of a certain attribute were analyzed, which were represented by R. R was used here instead of R^2 because it could show whether the slope of a changing trend was positive or negative. Note that the average NDWI and NDVI levels were represented by the average values from 1985 to 2015.

2.7 Influence of drought and climate warming

We analyzed the changes of NDWI and NDVI of SEGI groves and background areas during the 2011-2015 dry period and an earlier dry period (1987-1992). The two multi-year dry periods had very similar average precipitation (around 700 mm across SEGI groves), but the average annual mean temperature for 2011-2015 was about 1.5 ºC higher than for 1987-1992. We further examined how drought influenced SEGI groves and background areas at different elevation, TWI, average NDWI, and average NDVI levels. For this analysis, the four selected attributes (elevation, TWI, average NDWI, and average NDVI) were divided into three groups based on their histograms (Figure S5). We selected these four attributes because they were significant variables in the multivariate regression results (p-value<0.001) between 2011-2015 NDWI/NDVI changes and all available parameters in this study (including elevation, slope, aspect, TWI, average NDWI, and average NDVI), although the correlations were weak (R^2<0.08). Note that climate variables (mean temperature and total precipitation) were not included in the multivariate regression because of the mismatch of resolutions between PRISM data and other datasets.

3 Results

3.1 Overall trends

Areas within SEGI groves had higher NDWI and NDVI, slightly higher annual total precipitation and lower annual mean temperature than did background areas (Figure 2a-d). With average NDWI and NDVI of SEGI groves around 0.1 higher than those of background, SEGI groves were greener and wetter than non-grove forest. NDWI of both SEGI groves and background exhibited no temporal trends at the significance level of 0.05 but showed considerable interannual variability. NDVI in groves increased over the

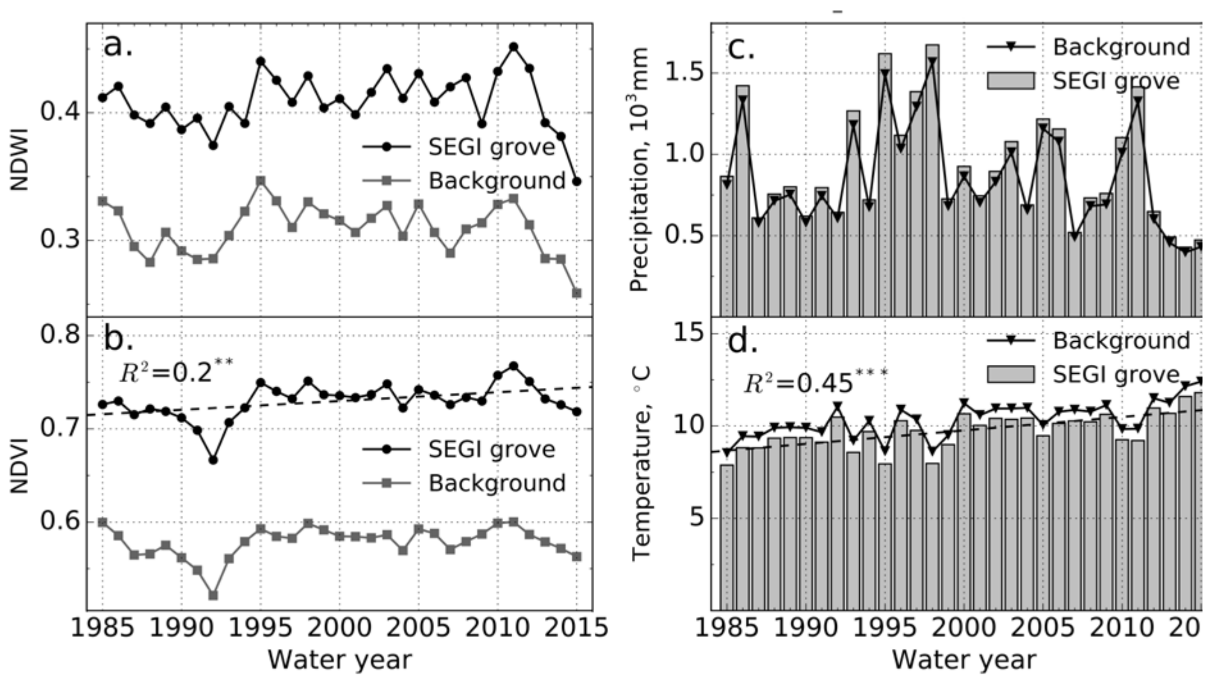

Figure 2. Annual water-year values of (a) NDWI, (b) NDVI, (c) precipitation, and (d) temperature from 1985 to 2015 for all 70 SEGI groves and background areas. If there is a significant linear correlation between a parameter and time, a dashed line is drawn and the corresponding R^2 value is noted with a label of confident level (* as 99.9%, ** as 99%, * as 95%, and ns as non-significant). Note that R^2 values for the 1985-2011 grove and background NDWI trends (prior to the 2011-2015 California drought) are 0.23 (**) and 0.06 (ns), and those for the 1985-2011 grove and background NDVI trends are 0.31(***) and 0.16 (*).**

past three decades, but no temporal trend was observed in background areas (Figure 2b). Prior to the 2011-2015 California drought, NDWI had an increasing trend (R^2=0.23**) in SEGI groves but no significant trend in background areas, and NDVI had increasing trends in both SEGI groves (R^2=0.31***) and background areas (R^2=0.16*) (Figure2). Individual groves exhibited NDWI trends that were both positive and negative (Table S1), corresponding to differing topographic and vegetation conditions. NDVI trends over 1985-2015 were positive in all but seven individual groves, four of which experienced at least one fire during the period (Tables S1 and S3). Wildfires with moderate and high severities brought abnormal drops to the NDWI and NDVI (Table S3). The NDVI of most groves experiencing wildfire recovered significantly in 3 years; however, the NDWI recovered much less (Table S3). The climate conditions of groves and background had similar trends. Annual water-year precipitation decreased slightly with time, but the trend was not significant (Figure 2c); while annual water-year temperature showed a significant increasing trend (Figure 2d). For the grove area, the annual water-year temperature increased by approximately 2.2 ºC from 1985 to 2015 based on a linear fit to the PRISM data, which was relatively larger than all the southern Sierra (Figure S6).

3.2 Factors influencing trends

Interannual fluctuations of NDWI within the grove area were correlated with both annual water-year precipitation (positively) and temperature (negatively) of the corresponding water year. Variations in NDVI had a positive correlation with precipitation but no significant correlation with temperature (Figure 3). Both precipitation and temperature had no significant lag effect on grove NDWI and NDVI (Table S4). The trends over 30 years of wetness (NDWI) and greenness (NDVI) differed with elevation and generally fell into three elevation zones (Figure 4). Below 1700 m, *R* values for grove NDWI and NDVI trends over time increased from negative or near-zero values to their maximum. For elevations of 1700-2100 m, *R* values for both grove NDWI and NDVI trends decreased, and *R* values for both grove NDWI and NDVI trends reached near zero

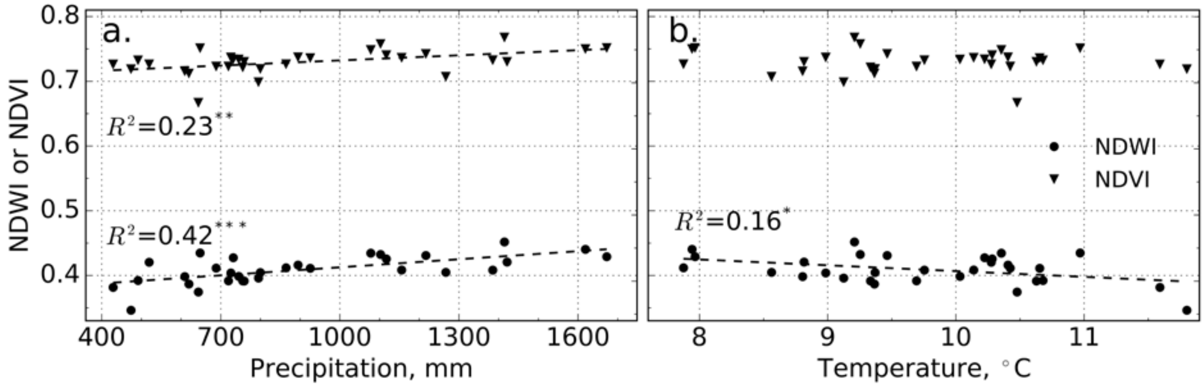

Figure 3. Correlations of annual water-year NDWI and NDVI with annual water-year (a) precipitation and (b) temperature, averaged from all 70 SEGI groves. Each dashed line represents a linear fit. R^2 values are labeled as significant at the confident level of 99.9% (***), significant at the confident level of 99% (**), significant at the confident level of 95% (*), and non-significant (ns).

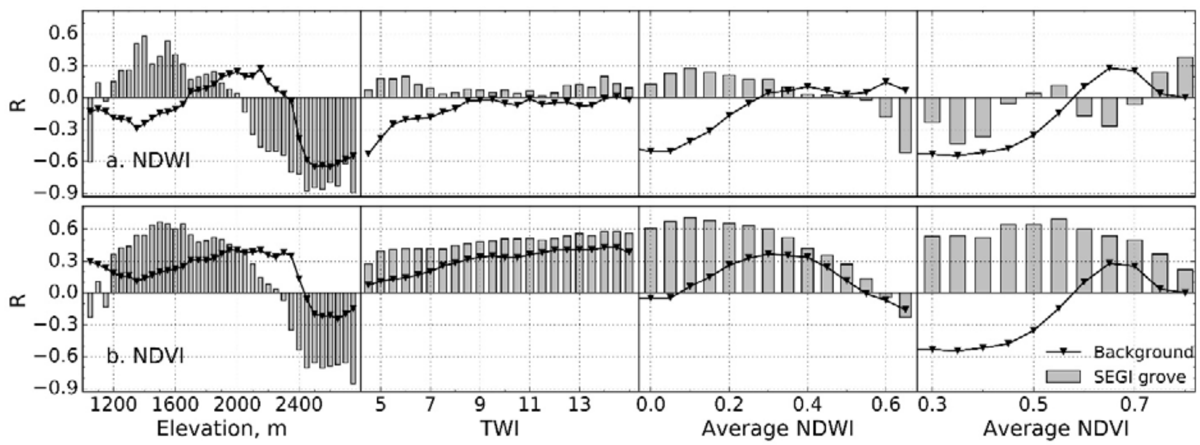

Figure 4. Correlation coefficients (*R* values) of (a) NDWI and (b) NDVI trends over time in SEGI groves and background areas for elevation zones (bins of 50 m), TWI zones (bins of 0.5), average 1985-2015 NDWI zones (bins of 0.05), and average 1985-2015 NDVI zones (bins of 0.05), respectively.

at 2000-2100 m. Above 2100 m, *R* values for trends in both grove NDWI and NDVI dropped to negative values, and reached the lowest values at the upper limit of grove elevations. The tends of background wetness and greenness were different (Figure 4). Below 1700 m, *R* values for background NDWI and NDVI trends were negative and positive, respectively, and they both first decreased and then increased slightly with elevation. For 1700-2100 m, *R* values for both background NDWI and NDVI trends over time increased and reached maximum values at about 2100 m. Above 2100 m, *R* values for both background NDWI and NDVI trends dropped, and reached near zero at 2300-2400 m.

TWI had no significant influence on the overall trends of NDWI and NDVI. *R* values for trends in grove NDWI stayed near zero values across all TWI zones, and *R* values for trends in grove NDVI slightly increased with TWI (Figure 4). However, for background areas, *R* values for NDWI and NDVI trends over time increased from negative (or near zero values) to positive (or near zero values) with higher TWI, and then became constant for TWI higher than 8.5. The trends in wetness and greenness of SEGI groves over time were negatively correlated with overall NDWI levels (*R* decreased as NDWI or NDVI increased), if we excluded non-vegetated areas (average NDWI < 0) (Figure 4). The trends for background wetness were generally positively correlated to average NDWI level, while *R* values for the trends in background greenness first increased with the average NDWI level (<0.4) and then decreased with the average NDWI level (>0.4) (Figure 4). The overall NDVI level had a similar relation to trends in wetness and greenness of both SEGI groves and background areas. *R* values for grove NDWI, grove NDVI, background NDWI, and background NDVI trends all increased with the average NDVI level (Figure 4).

3.3 Influence of drought and climate warming

Both grove and background NDWI and NDVI have a significant drop during the 2011-2015 drought (*p*-value<0.001), but the drop of NDWI was much larger than the drop of NDVI (Figure 5). The drop of NDWI in SEGI groves was greater than in background areas, while the drop of NDVI in SEGI groves was similar to that in background areas. In both groves and background areas, the decline in NDWI and NDVI were lower at higher elevations. Declines in NDWI and NDVI were slightly lower in areas with higher versus lower TWI. Grove and background areas with higher average NDWI had a greater drop in NDWI during the drought, with drops in NDVI more apparent in areas with higher average NDWI. Both SEGI groves and background areas with mid values of NDVI had the largest drops in NDWI.

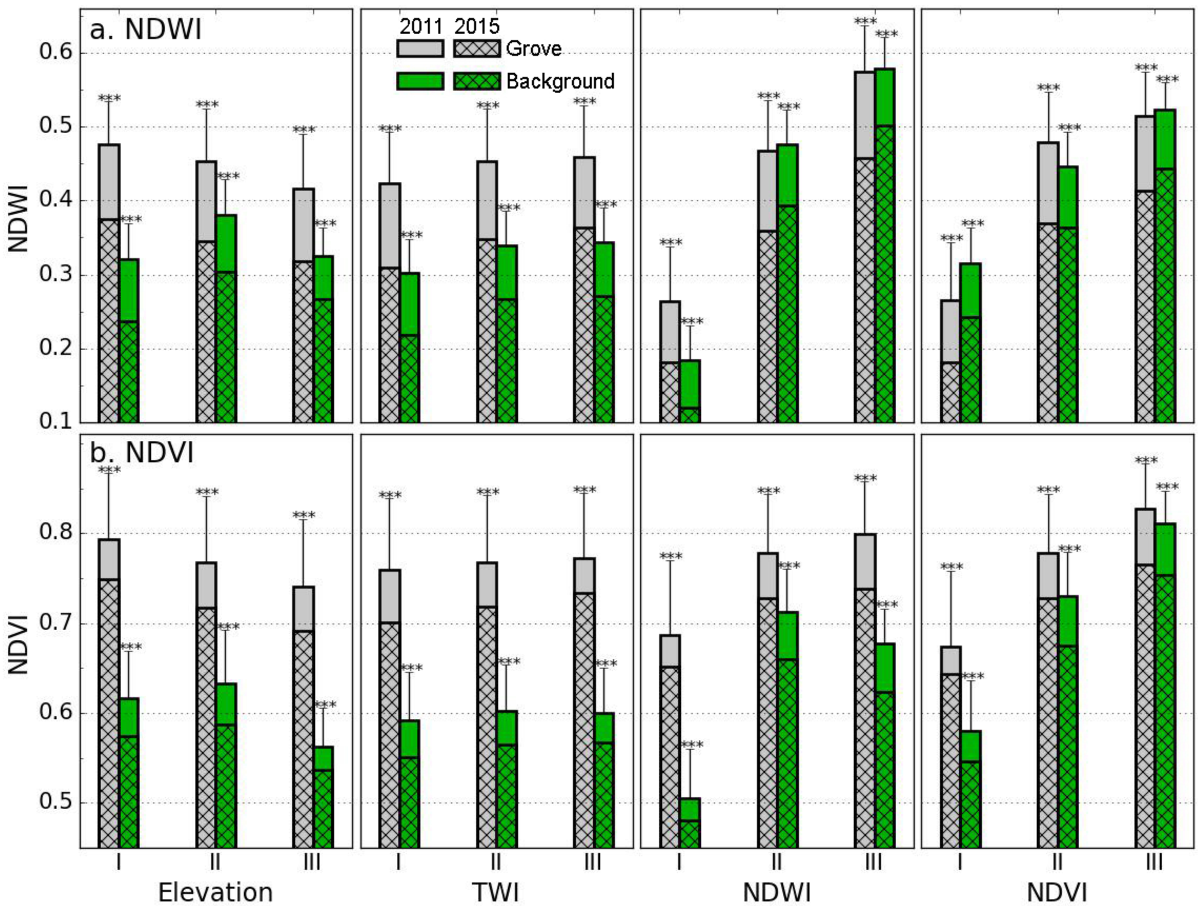

Figure 5. (a) NDWI and (b) NDVI differences (2011 versus 2015) of SEGI grove and background area for three elevation bins (Zone I <1751 m, Zone II 1751-2103 m, Zone III ≥ 2103 m), three TWI bins (Zone I <6.97, Zone II 6.97-10.13, Zone III ≥ 10.13), three average 1985-2015 NDWI bins (Zone I <0.31, Zone II 0.31-0.51, Zone III ≥ 0.51), and three average 1985-2015 NDVI bins (Zone I <0.69, Zone II 0.69-0.79, Zone III ≥ 0.79). The error bar represents the standard deviation of the NDWI or NDVI change between 2011 and 2015. The significance of differences between 2011 and 2015 NDWI or NDVI are noted with a label of confident level (* as 99.9%, ** as 99%, * as 95%, and ns as non-significant). The three zones of the corresponding factor were divided based on mean ± standard deviation (Figure S5).**

The average annual precipitation during 1987-1992 and 2011-2015 dry periods were very close (about 700 mm), but the average annual mean temperature for 2011-2015 was about 1.5ºC higher than for 1987-1992. The annual decline in grove NDWI for 2011-2015 was much greater than for 1987-1992 (Figure 6a). Despite the different magnitudes of NDWI decline between time periods, the pattern of NDWI change with elevation was similar. For each dry period, the drops in grove NDWI varied little with elevation below about 2100-2300 m, and were smaller above those elevations. For 2011-2015, areas with higher TWI had lower annual declines in NDWI than lower TWI areas. The dependence of NDWI decline on TWI was not apparent in 1987-1992, possibly because NDWI declines were too small. The shapes of the relationships between average NDWI and NDVI levels and the annual drop of grove NDWI were similar for both periods. The higher the average NDWI or NDVI level, the greater the decline in NDWI, with this pattern much stronger for 2011-2015, which had overall larger drops in NDWI than the earlier time period. However, the relative decline rate decreased with the average NDWI or NDVI level (Figure S7a).

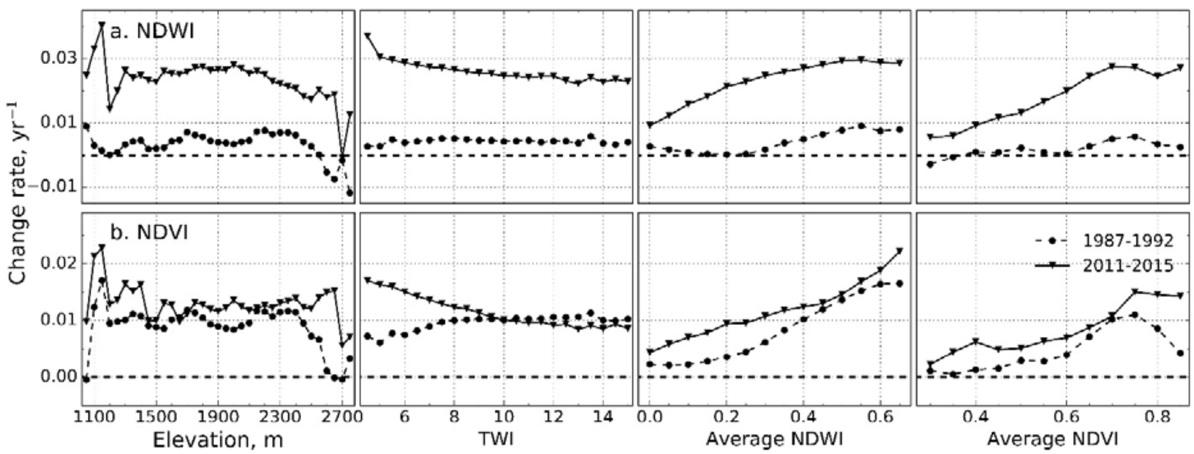

Figure 6. Changes in (a) NDWI and (b) NDVI during two dry periods (1987-1992 and 2011-2015) in SEGI groves for elevation zones displaced every 50 m, TWI zones displaced every 0.5, average 1985-2015 NDWI zones displaced every 0.05, and average 1985-2015 NDVI zones displaced every 0.05. Note that the annual NDWI and NDVI change was calculated as the difference between the first year (i.e., 1987 and 2011) and last year (i.e., 1992 and 2015) divided by the length of a dry period.

The annual decline in NDVI for 2011-2015 was slightly higher than for 1987-1992 (Figure 6b). The annual NDVI decline for 2011-2015 stayed relatively constant across elevations, except for a shift toward less change at elevations above around 2500 m for 1987-1992 and 2700 m for 2011-2015. Areas with higher TWI had lower annual declines in NDVI during 2011-2015, while annual NDVI decline stayed relatively constant with TWI for 1987-1992. The drop in NDVI generally rose as average NDWI or NDVI increased, except for the highest average NDVI categories above 0.7. This pattern was in consistent with the relative change rate (Figure S7b).

4 Discussion

4.1 Overall trends

Although both greenness and temperature in SEGI groves showed significant increases during the last three decades (Figure 2b), they were not correlated. This points to multiple factors being responsible for the increase in NDVI, including temperature, precipitation and management actions [*Stephenson,* 1996]. Based on the strong correlation between annual mean NDVI and annual evapotranspiration for the western slopes of the Sierra Nevada developed by *Goulden et al.* [2012], the observed increase of NDVI over the past 30 years could result in a 70-80 mm yr^{-1} rise in annual evapotranspiration, corresponding to an 800 mm yr^{-1} total annual evapotranspiration in the elevation zone of SEGI groves. If we excluded the

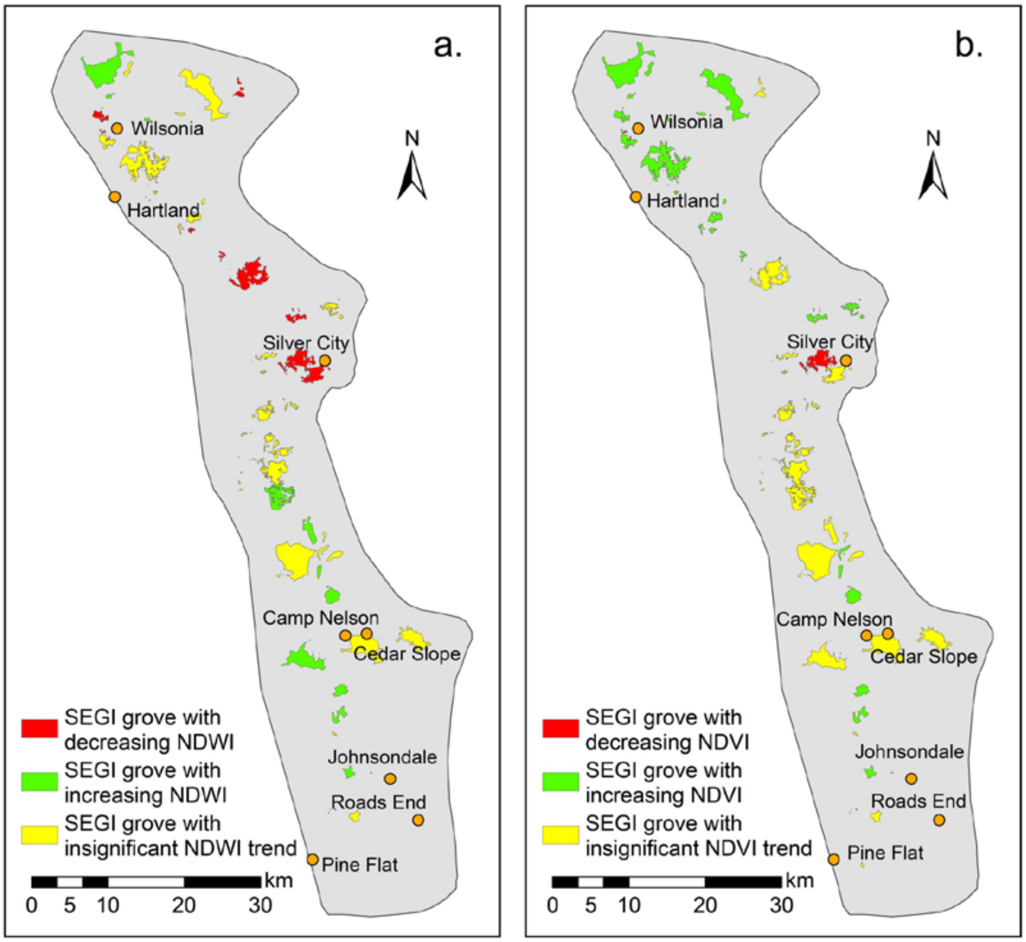

Figure 7. The distribution of SEGI groves with a decreasing, increasing, or insignificant trend in (a) NDWI and (b) NDVI during the last three decades.

recent California drought period, the observed increase of NDVI for 1985-2011 corresponds to a nearly 100 mm yr^{-1} rise in annual evapotranspiration. This evapotranspiration increase would have a commensurate effect on stream discharge. Over longer time periods, the increase of NDVI and thus tree density on the western slopes of the Sierra Nevada is attributed in part to fire suppression [*Stephens et al.*, 2010; *Su et al.*, 2016a]. By comparing Vegetation Type Mapping plots in the 1930s with Forest Inventory and Analysis plots in the 2000s, *Dolanc et al.* [2014] found that tree density on the western slopes of the Sierra Nevada had a 50% increase on average. In the mixed conifer forests of the southern Sierra Nevada, the tree density has nearly been tripled since 1911 [*Stephens et al.*, 2015]. Although there is no significant overall trend for SEGI grove NDWI, the interannual fluctuations of SEGI grove NDWI were positively correlated with precipitation and negatively correlated with temperature in the same water year (Figure 3a). These results are in consistence with previous findings [*Trujillo et al.*, 2012].

Compared to background areas, the NDWI and NDVI for SEGI groves are generally higher than for background areas (Figures 2a and 2b). This might be related to the fact the TWI values of SEGI groves are generally higher than for background areas. It is known that SEGI trees prefer a moist habitat [*Harvey et al.*, 1980; *Rundel*, 1971]. TWI is a measure of the potential for a landscape to hold water based on its surface characteristics, and can be used as a proxy for actual soil moisture at the landscape scale [*Beven and Kirkby*, 1979]. Therefore, a higher TWI can possibly lead to a moister habitat for SEGI trees, and may serve as climate-change "hydrologic" refugia within the large mixed-conifer forest [*McLaughlin et al.*, 2017, *Maher et al.*, 2017].

4.2 Factors influencing trends

SEGI groves at different elevations responded differently to the variables and changing climate. The wetness and greenness both decreased over 1985-2015 in higher-elevation groves (Figure 4). This may be one of the main reasons why groves with significantly decreasing NDWI and NDVI were geographically concentrated in the center of SEGI domain (Figure 7). The average elevation of groves with significantly decreasing NDWI is about 200 m higher than other groves, and the average elevation of groves with significantly decreasing NDVI is over 350 m higher than other groves. Elevations of 1700 m and 2100 m mark two important transitions for the responses of SEGI groves: lower limit and approximate mid-point of the rain-snow transition zone, with 2100 m being the elevation of about 50% precipitation as snow [*Halpin,* 1995; *Kirchner et al.,* 2014; *Rice et al.*, 2011]. This result is consistent with the findings in the Upper Kings River basin which is adjacent to the SEGI domain [*Potter,* 2015] (Figure S4). Through examining the NDVI derived from 1986-2013 Landsat TM images, *Potter* [2015] found that the NDVI increase mainly concentrated in areas with an elevation lower than 2000 m; while for the areas with an elevation higher than 2000 m, NDVI has not risen during this period.

It is expected that the warming climate can boost the growth and recruitment of trees in higher elevation areas, since they are more energy limited [*Korner,* 2012; *Rossi et al.,* 2008; *Trujillo et al.,* 2012]. However, the finding in this study on SEGI groves and the surrounding forest is contrary to this expectation. We found that NDVI and NDWI declined over the period 1985-2015 in higher-elevation grove areas, while they generally increased in the lower elevations. A recent study by *Kuppers et al.* [2016] found that the seeding and recruitment of subalpine conifers at higher elevations are more negatively influenced by the rising temperature than at low elevations based on field observations, and there have been studies showing the negative response of NDVI temporal change to elevation [*Piao et al.,* 2011; *Gamon et al.,* 2013]. The reason for this phenomenon is currently unclear. A possible explanation may be that tree distributions at upper and lower elevations have different sensitivities to temperature and precipitation [*Morgan et al.*, 2014; *Kuppers et al.*, 2016]. Above the 1700-2100 m elevation zone, snowmelt stored in the regolith over summer is the main summer-fall water source for SEGI trees. Although annual water-year precipitation did not show a significant trend during the last three decades, the average annual water-year temperature increased by about 2.2 ºC (Figure 2). The increasing temperature resulted in earlier snowmelt and longer dry seasons in areas with elevations higher than the transition zone [*Trujillo et al.,* 2012], potentially leading to decreasing grove wetness and greenness. At elevations below this range, where a greater proportion of precipitation fell as rain, SEGI trees may be more adapted to the long and dry summers and therefore be less sensitive to earlier snowmelt [*Trujillo et al.,* 2012]. Moreover, the larger extent of wildfire in the upper-elevation zone may further influence this pattern since forest fires can cause significant declines in grove NDWI and NDVI (Table S3).

4.3 Influence of drought and climate warming

The wetness of SEGI groves is very sensitive to drought. The influence of droughts on the wetness of SEGI groves reflected effects of both the multi-decadal increase in forest biomass and the effects of warmer drought-year temperatures on the evaporative demand of current grove vegetation, versus available regolith water storage of rain and snowmelt to sustain that vegetation through dry periods.

The NDWI of SEGI groves dropped an average of 25% during the 2011-2015 dry period, a 50% greater response than that in background areas. This may be caused by the fact the average NDWI level for SEGI groves is higher than background areas, indicating that there may be more water to lose in SEGI canopy. Additionally, although the wetness and greenness of lower-elevation groves increased with the warming climate in the past 30 years (Figure 4), their resiliency to multi-year drought may be relatively lower compared to higher-elevation groves. The drop of grove wetness during the dry period decreased slightly with elevation, and this effect is more pronounced in non-grove areas (Figure 5a and Figure 6a). Finally, the greater drop in NDVI and especially NDWI that occurred during the warmer 2011-2015 dry period compared to the 1987-1992 dry period, demonstrates that increasing temperature can intensify the influence of extreme droughts on the SEGI groves.

We view our study as a small but important step forward understanding how the SEGI groves respond to changing climate across their native range. Our analysis relied on the time-series Landsat images, whose limitations include a 30-m spatial resolution that is too coarse to separate the response of SEGI trees versus other trees. This spatial resolution means that grove areas include canopies of co-occurring tree species in addition to sequoias. Thus, our analysis focused on grove versus non-grove areas. Although there are advantages of supplementing hyperspectral and airborne light detection and ranging (LiDAR) data to map forest-canopy water [*Asner et al.*, 2016], these data are only available in a very limited time window. Landsat images were the only choice for such a long-term analysis. Future work is needed to combine the long-term Landsat images with other high-fidelity remotely sensed datasets (e.g., hyperspectral data and LiDAR) and ground-based water-balance measurements to quantify the change in SEGI canopy water content, absolute water storage, and evapotranspiration, and therefore build a capability to predict the risk to SEGI groves in face of the warming climate and the responses of groves to management activities to influence evapotranspiration and drought response.

Existing policies are failing to conserve old trees, and new policies on long-term protection, recruitment, and maintenance of an age structure are needed [*Lindenmayer et al.*, 2014]. Our findings on the changing patterns of SEGI grove wetness and greenness and the responses of SEGI groves to droughts can help forest managers to distribute the limited resources to protect area of interest. Grove greenness, wetness, as well as forest structures [*Stephenson*, 1999] can inform efforts to restore and protect SEGI trees.

5 Conclusions

Although SEGI groves have thus far been spared the widespread conifer mortality in drier and lower elevations of the southern Sierra, there are signs of stress. First, over the last three decades, the greenness of SEGI groves has increased significantly, indicating an increase in forest biomass, and thus in vegetation density and evapotranspiration. While grove wetness shows no significant 30-yr trend, it does positively respond to annual water-year precipitation and negatively respond to temperature. The increase in evapotranspiration indicated by the increasing biomass, with an increase in temperature but not in precipitation, signifies an increasing vulnerability to multi-year dry periods, when multi-year subsurface water stage may be insufficient to make up for lower precipitation. Second, the wetness and greenness changes in SEGI groves from 1985 to 2015 are distinct from non-grove areas; and overall, the greenness and wetness of SEGI groves are more sensitive to a warming climate than non-grove areas. The 2011-2015 drought has brought a drop in grove wetness five times the normal variance from 1985 to 2010. The 2011-2015 change in grove wetness was over 50% greater than in surrounding non-grove areas, suggesting that while SEGI groves currently might serve as climate change "hydrologic" refugia within the larger mixed-conifer forest, but their refugial properties may be eroding. Reducing tree density by appropriate forest management actions may help to preserve their refugial properties. Third, changes in grove wetness and greenness are elevation dependent. Below the lower rain-snow transition elevation zone (1700 – 2100 m), there is a dominant increasing trend in grove wetness and greenness over the past three decades; above this elevation zone, there is a decreasing trend. Moreover, groves at lower elevation and with lower TWI can have a greater loss of grove wetness in a warm drought.

Acknowledgments

Research was supported in part by the Sequoia and Kings Canyon National Parks, and in part by the National Science Foundation through the Southern Sierra Critical Zone Observatory (EAR- 1239521). The SEGI domain boundary, SEGI grove boundary, and all generated Landsat NDVI and NDWI products are available through ftp://share.3decology.org/SEGI/, and the SRTM DEM data, PRISM climate surfaces, and MTBS fire severity data can be downloaded from https://earthexplorer.usgs.gov/, http://prism.oregonstate.edu/explorer/, and https://www.mtbs.gov/, respectively.

References

Ambrose, A.R., Baxter, W.L., Wong, C.S., Naesborg, R.R., Williams, C.B., & Dawson, T.E. (2015). Contrasting drought-response strategies in California redwoods. Tree Physiology, 35, 453-469

Anderson, M., Graham, R., Alyanakian, G., & Martynn, D. (1995). Late summer water status of soils and weathered bedrock in a giant sequoia grove. Soil Science, 160, 415-422

Asner, G.P., Brodrick, P.G., Anderson, C.B., Vaughn, N., Knapp, D.E., & Martin, R.E. (2016). Progressive forest canopy water loss during the 2012-2015 California drought. Proceedings of the National Academy of Sciences of the United States of America, 113, E249-255

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

Beven, K.J., & Kirkby, M.J. (1979). A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. Hydrological Sciences Bulletin, 24, 43-69

Claverie, M., Vermote, E.F., Franch, B., & Masek, J.G. (2015). Evaluation of the Landsat-5 TM and Landsat-7 ETM+ surface reflectance products. Remote Sensing of Environment, 169, 390-403

Carlson, T.N., Capehart, W.J., & Gillies, R.R. (1995). A New Look at the Simplified Method for Remote-Sensing of Daily Evapotranspiration. Remote Sensing of Environment, 54, 161-167

Cook, L. (1955). Giant Sequoias of California. United States Government Printing Office

Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J., & Pasteris, P.P. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology, 28, 2031-2064

Das, A.J., Stephenson, N.L., Flint, A., Das, T., & Van Mantgem, P.J. (2013). Climatic correlates of tree mortality in water-and energy-limited forests. PloS One, 8, e69917

Delbart, N., Le Toan, T., Kergoat, L., & Fedotova, V. (2006). Remote sensing of spring phenology in boreal regions: A free of snow-effect method using NOAA-AVHRR and SPOT-VGT data (1982–2004). Remote Sensing of Environment, 101, 52-62

Diffenbaugh, N.S., Swain, D.L., & Touma, D. (2015). Anthropogenic warming has increased drought risk in California. Proceedings of the National Academy of Sciences of the United States of America, 112, 3931-3936

Dolanc, C.R., Safford, H.D., Thorne, J.H., & Dobrowski, S.Z. (2014). Changing forest structure across the landscape of the Sierra Nevada, CA, USA, since the 1930s. Ecosphere, 5, art101

Douglass, A. E. (1925). Tree Rings and Climate, The Scientific Monthly, 21, 95-99

Eidenshink, J.C., Schwind, B., Brewer, K., Zhu, Z.-L., Quayle, B., & Howard, S.M. (2007). A project for monitoring trends in burn severity. Fire Ecology, 3, 3-21

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., & Roth, L. (2007). The shuttle radar topography mission. Reviews of geophysics, 45, RG2004

Gamon, J.A., Huemmrich, K.F., Stone, R.S., & Tweedie, C.E. (2013). Spatial and temporal variation in primary productivity (NDVI) of coastal Alaskan tundra: Decreased vegetation growth following earlier snowmelt. Remote Sensing of Environment, 129, 144-153

Gao, B.C. (1996). NDWI - A normalized difference water index for remote sensing of vegetation liquid water from space. Remote Sensing of Environment, 58, 257-266

Goulden, M.L., Anderson, R.G., Bales, R.C., Kelly, A.E., Meadows, M., & Winston, G.C. (2012). Evapotranspiration along an elevation gradient in California's Sierra Nevada. Journal of Geophysical Research-Biogeosciences, 117, G03028

Goulden, M.L., & Bales, R.C. (2014). Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion. Proceedings of the National Academy of Sciences of the United States of America, 111, 14071-14075

Gu, Y., Hunt, E., Wardlow, B., Basara, J.B., Brown, J.F., & Verdin, J.P. (2008). Evaluation of MODIS NDVI and NDWI for vegetation drought monitoring using Oklahoma Mesonet soil moisture data. Geophysical Research Letters, 35, L22041

Halpin, P.N. (1995). A cross-scale analysis of environmental gradients and forest pattern in the giant sequoia-mixed conifer forest of the Sierra Nevada, University of Virginia (Ph.D. dissertation)

Harvey, H., Shellhammer, H., & Stecker, R. (1980). Giant sequoia ecology: fire and reproduction. In, Giant sequoia ecology

Holben, B.N. (1986). Characteristics of maximum-value composite images from temporal AVHRR data. International Journal of Remote Sensing, 7, 1417-1434

Hughes, M.K., & Brown, P.M. (1992). Drought frequency in central California since 101 BC recorded in giant sequoia tree rings. Climate Dynamics, 6, 161-167

Jackson, T.J., Chen, D.Y., Cosh, M., Li, F.Q., Anderson, M., Walthall, C., Doriaswamy, P., & Hunt, E.R. (2004). Vegetation water content mapping using Landsat data derived normalized difference water index for corn and soybeans. Remote Sensing of Environment, 92, 475-482

Kirchner, P.B., Bales, R.C., Molotch, N.P., Flanagan, J., & Guo, Q. (2014). LiDAR measurement of seasonal snow accumulation along an elevation gradient in the southern Sierra Nevada, California. Hydrology and Earth System Sciences, 18, 4261-4275

Kitzmiller, J.H., & Lunak, G. (2012). Growth of Giant Sequoia Compared to Ponderosa Pine and Other Mixed-Conifers in California Plantations. Western Journal of Applied Forestry, 27, 196-204

Korner C. (2012). Alpine Treelines: Functional Ecology of the Global High Elevation Tree Limits. Springer, Basel.

Kueppers, L.M., Conlisk, E., Castanha, C., Moyes, A.B., Germino, M.J., Valpine, P., Torn, M.S., & Mitton, J.B. (2016). Warming and provenance limit tree recruitment across and beyond the elevation range of subalpine forest. Global Change Biology, doi: 10.1111/gcb.13561

Li, P., Jiang, L., & Feng, Z. (2013). Cross-comparison of vegetation indices derived from landsat-7 enhanced thematic mapper plus (ETM+) and landsat-8 operational land imager (OLI) sensors. Remote Sensing, 6, 310-329

Lindenmayer, D.B., Laurance, W.F., Franklin, J.F., Likens, G.E., Banks, S.C., Blanchard, W., Gibbons, P., Ikin, K., Blair, D., McBurney, L. and Manning, A.D., (2014). New policies for old trees: averting a global crisis in a keystone ecological structure. Conservation Letters, 7, 61-69.

Maher, S.P., Morelli, T.L., Hershey, M., Flint, A.L., Flint, L.E., Moritz, C., & Beissinger, S.R. (2017). Erosion of refugia in the Sierra Nevada meadows network with climate change. Ecosphere, 8, e01673.

Masek, J., Vermote, E., Saleous, N., Wolfe, R., Hall, F., Huemmrich, F., Gao, F., Kutler, J., & Lim, T. (2013). LEDAPS calibration, reflectance, atmospheric correction preprocessing code, version 2. Model product

McLaughlin, B.C., Ackerly, D.D., Klos, P.Z., Natali, J., Dawson, T.E., & Thompson, S.E. (2017). Hydrologic refugia, plants, and climate change. Global Change Biology, doi: 10.1111/gcb.13629.

Meyer, M.D., & Safford, H.D. (2011). Giant Sequoia Regeneration in Groves Exposed to Wildfire and Retention Harvest. Fire Ecology, 7, 2-16

Millar, C.I. 1996. Tertiary vegetation history. Chapter 5 in Sierra Nevada Ecosystem Project, Final report to Congress, Volume II, Assessments and Scientific Basis for Management Options, Centers for Water and Wildland Resources, Report No. 37, University of California, Davis, California, 71-122

Millar, C.I. 2003. Climate change as an ecosystem architect: Implications to rare plant ecology, conservation, and management. In: Brooks, M. (ed). Proceedings of the Conference on Rare Plants, Ecology, and Conservation, 9-13 Feb 2002, Arcata, California. California Native Plant Society, 139-157

Morgan, C., Losey, A., & Trout, L. (2014). Late-Holocene paleoclimate and treeline fluctuation in Wyoming's Wind River Range, USA. The Holocene, 24, 209-219

Mooney, H. (1977). Convergent evolution in Chile and California: Mediterranean climate ecosystems. Stroudsburg, Pennsylvania: Dowden, Hutchinson & Ross, Inc.

Mutch, L. (1994). Growth responses of giant sequoia to fire and climate in Sequoia and Kings Canyon National Parks, California, University of Arizona (master thesis)

Piao, S., Cui, M., Chen, A., Wang, X., Ciais, P., Liu, J., & Tang, Y. (2011). Altitude and temperature dependence of change in the spring vegetation green-up date from 1982 to 2006 in the Qinghai-Xizang Plateau. Agricultural and Forest Meteorology, 151, 1599-1608

Potter, C. (2015). Vegetation cover change in the Upper Kings River basin of the Sierra Nevada detected using Landsat satellite image analysis. Climatic Change, 131, 635-647

Rice, R., Bales, R.C., Painter, T.H., & Dozier, J. (2011). Snow water equivalent along elevation gradients in the Merced and Tuolumne River basins of the Sierra Nevada. Water Resources Research, 47

Rossi, S., Deslauriers, A., Griçar, J., Seo, J.W., Rathgeber, C.B., Anfodillo, T., Morin, H., Levanic, T., Oven, P., & Jalkanen, R. (2008). Critical temperatures for xylogenesis in conifers of cold climates. Global ecology and biogeography, 17, 696-707

Rundel, P.W. (1971). Community structure and stability in the giant sequoia groves of the Sierra Nevada, California. American Midland Naturalist, 85, 478-492

Sillett, S. C., R. Van Pelt, A. L. Carroll, R. D. Kramer, A. R. Ambrose, and D. A. Trask (2015). How do tree structure and old age affect growth potential of California redwoods? Ecological Monographs, 85, 181-212

Stephenson, N. L. (1994), Long-term dynamics of giant sequoia populations: implications for managing a pioneer species, paper presented at Proceedings of the symposium on giant sequoias: Their place in the ecosystem and society (Tech. coord. P Aune)

Stephens, S.L., Millar, C.I., & Collins, B.M. (2010). Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates. Environmental Research Letters, 5, 024003

Stephenson, N. L. 1996. Ecology and management of giant sequoia groves. in Sierra Nevada Ecosystem Project: final report to Congress, volume II. Assessments and scientific basis for management options. Centers for Water and Wildland Resources Report no. 37, University of California, Davis, California, USA

Stephenson, N.L. (1999). Reference conditions for giant sequoia forest restoration: structure, process, and precision. Ecological Applications, 9, 1253-1265

Stephens, S. L., J. M. Lydersen, B. M. Collins, D. L. Fry, and M. D. Meyer (2015). Historical and current landscape-scale ponderosa pine and mixed conifer forest structure in the Southern Sierra Nevada, Ecosphere, 6, 1-63

Su, Y., Guo, Q., Collions, B.M., Fry, D.L., Hu, T., & Kelly, M. (2016a). Forest fuel treatment detection using multi-temporal airborne lidar data and high-resolution aerial imagery: a case study in the Sierra Nevada Mountains, California. International Journal of Remote Sensing, 37, 3322-3345

Su, Y., Guo, Q., Ma, Q., & Li, W. (2015). SRTM DEM Correction in Vegetated Mountain Areas through the Integration of Spaceborne LiDAR, Airborne LiDAR, and Optical Imagery. Remote Sensing, 7, 11202-11225

Su, Y., Guo, Q., Xue, B., Hu, T., & Alvarez, O. (2016b). Spatial distribution of forest aboveground biomass in China: Estimation through combination of spaceborne lidar, optical imagery, and forest inventory data. Remote Sensing of Environment, 173, 187-199

Sulla-Menashe, D., Friedl, M. A., & Woodcock, C. E. (2016). Sources of bias and variability in long-term Landsat time series over Canadian boreal forests. Remote Sensing of Environment, 177, 206-219

Swetnam, T.W. (1993). Fire history and climate change in giant sequoia groves. Science, 262, 885-889

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

van Mantgem, P.J., Caprio, A.C., Stephenson, N.L., & Das, A.J. (2016). Does prescribed fire promote resistance to drought in low elevation forests of the Sierra Nevada, California, USA? Fire ecology, 12, 13-25

van Leeuwen, W.J.D., Huete, A.R., & Laing, T.W. (1999). MODIS Vegetation Index Compositing Approach. Remote Sensing of Environment, 69, 264-280

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

Williams, A.P., Seager, R., Abatzoglou, J.T., Cook, B.I., Smerdon, J.E., & Cook, E.R. (2015). Contribution of anthropogenic warming to California drought during 2012-2014. Geophysical Research Letters, 42, 6819-6828

Wittstock, T., Zimmermann, R., & Aas, G. (2012). Influence of site climate on the radial growth of Sequoiadendron giganteum and Picea abies. Allgemeine Forst Und Jagdzeitung, 183, 55-62

York, R.A., Battles, J.J., & Heald, R.C. (2006). Release potential of giant sequoia following heavy suppression: 20-year results. Forest Ecology and Management, 234, 136-142

York, R.A., Fuchs, D., Battles, J.J., & Stephens, S.L. (2010). Radial growth responses to gap creation in large, old Sequoiadendron giganteum. Applied Vegetation Science, 13, 498-509

York, R.A., Louen, J.M., & Thomson, A.C. (2015). Growth Response of Massive Sequoiadendron giganteum Trees to Mechanical Treatments. Forest Science, 61, 959-965

York, R. A., Stephenson N. L., Meyer M., Hanna S., Moody T., Caprio A. C., and Battles J. J. (2013a). A natural resource condition assessment for Sequoia and Kings Canyon National Parks: Appendix 11a – giant sequoias. Natural Resource Report NPS/SEKI/NRR—2013/665.11a. National Park Service, Fort Collins, Colorado

York, R.A., O'Hara, K.L., & Battles, J.J. (2013b). Density Effects on Giant Sequoia (Sequoiadendron giganteum) Growth Through 22 Years: Implications for Restoration and Plantation Management. Western Journal of Applied Forestry, 28, 30-36

Zheng, D.L., Rademacher, J., Chen, J.Q., Crow, T., Bresee, M., le Moine, J., & Ryu, S.R. (2004). Estimating aboveground biomass using Landsat 7 ETM+ data across a managed landscape in northern Wisconsin, USA. Remote Sensing of Environment, 93, 402-411