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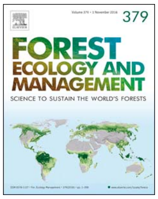

Patterns and correlates of giant sequoia foliage dieback during California's 2012–2016 hotter drought

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ABSTRACT

Hotter droughts – droughts in which unusually high temperatures exacerbate the effects of low precipitation – are expected to increase in frequency and severity in coming decades, challenging scientists and managers to identify which parts of forested landscapes may be most vulnerable. In 2014, in the middle of California's historically unprecedented 2012–2016 hotter drought, we noticed apparently drought-induced foliage dieback in giant sequoias (*Sequoiadendron giganteum* Lindl. [Buchholz]) in Sequoia and Kings Canyon national parks, California. Characteristics of the dieback were consistent with a controlled process of drought-induced senescence: younger (distal) shoots remained green while older (proximal) shoots were preferentially shed. As part of an ongoing interdisciplinary effort to understand and map sequoia vulnerability to hotter droughts, we reviewed historical records for evidence of previous foliage dieback events, surveyed dieback along trail corridors in eight sequoia groves, and analyzed tree-ring data from a high- and a low-foliage-dieback area. In sharp contrast to the greatly elevated mortality of other coniferous species found at low and middle elevations, we estimate that < 1% of sequoias died during the drought. Foliage dieback was notably elevated in 2014 – the most severe single drought year in our 122-year record – but much lower in subsequent years. We found no historical records of similar foliage dieback during previous droughts. Dieback in 2014 was highly variable both within and among groves, ranging from virtually no dieback in some areas to nearly 50% in others. Dieback was highest (1) at low elevations, probably due to higher temperatures, reduced snowpack, and earlier snowmelt; (2) in areas of low adult sequoia densities, which likely reflect intrinsically more stressful sites; and (3) on steep slopes, probably reflecting reduced water availability. Average sequoia ring widths were narrower at the high-dieback than the low-dieback tree-ring site, but for reasons that remain unclear the sites did not differ in their proportional ring-width responses to past droughts. Collectively, our results suggest that giant sequoia vulnerability to hotter droughts may be spatially quite variable, and that at least some of that variability can be explained by metrics related to site water balance. Future research will focus on integrating our results with physiological and remote-sensing data, including tracking sequoias as they recover from the drought.

1. Introduction

Hotter droughts (also called "global-change-type droughts" or "hot droughts") are an emerging climate-change threat to forests, with some of their earliest and strongest manifestations seen in greatly elevated tree mortality in the American Southwest (Breshears et al., 2005; Allen et al., 2010, 2015; Williams et al., 2013). In hotter droughts, unusually high temperatures exacerbate the effects of low precipitation, most likely through a combination of direct and indirect effects such as temperature-induced increases in vapor pressure deficit, increased leaf heating that is not offset by evaporative cooling, declining snowpack water content and earlier melt, and enhanced effectiveness of insects that attack trees. If global temperatures continue to rise as projected, the future is likely to hold more frequent and more severe hotter droughts (Allen et al., 2015).

Fortunately, forest managers may be able to enhance tree survival in

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the face of future hotter droughts (e.g. van Mantgem et al., 2016). For example, forests can be thinned – usually by prescribed fire or mechanical thinning – to reduce competition for water among the remaining trees. But the task is so vast that forest managers will need to perform triage, deciding where on the landscape their limited efforts will be best applied (Nydick et al., this issue). Effective forest management thus requires reliable forest vulnerability maps to help strategically target treatments.

Forest managers in California's Sierra Nevada have been particularly interested in developing vulnerability maps for the iconic giant sequoia (*Sequoiadendron giganteum* Lindl. [Buchholz]), which occurs mixed with other tree species in ~70 scattered groves that collectively occupy about 14,600 ha (Stephenson, 1996). During California's 2012–2016 hotter drought – the most extreme in the instrumental record and perhaps in the last several centuries (Diffenbaugh et al., 2015; Williams et al., 2015) – we noticed apparently drought-induced foliage dieback in sequoias, something that had never before been recorded. As part of a broader effort to understand and map sequoia vulnerability to hotter droughts of the future (Stephenson et al., 2016), we sought to document and interpret the dieback.

Specifically, we wished to (1) describe spatial patterns of drought-induced foliage dieback, both within and among sequoia groves, (2) explore local environmental correlates of the spatial patterns, (3) in a high-dieback and a low-dieback area, use sequoia tree rings to compare and contrast growth responses to past droughts, (4) describe temporal variation in foliage dieback over four consecutive years, and (5) discuss the implications of our results for understanding sequoia vulnerability to hotter droughts of the future.

2. Methods

2.1. Study site

Found only in California's Sierra Nevada, the ~70 naturally-occurring giant sequoia groves are those parts of white fir - mixed conifer forest that contain giant sequoias, and tend to occur on sites with more available soil moisture than the surrounding forest (Rundel, 1972a, 1972b; Stephenson, 1996; Willard, 2000). Numerically, most groves are overwhelmingly dominated by white fir (*Abies concolor*), with sugar pine (*Pinus lambertiana*) commonly being the next most abundant species, followed by giant sequoia and other species (Rundel, 1971).

Our field work was conducted in eight sequoia groves within Sequoia and Kings Canyon national parks, in the southern Sierra Nevada (Table 1; Fig. S1). Mean grove elevations ranged from 1850 m to 2201 m. At these elevations the climate is montane mediterranean, with cool, wet winters in which roughly half of precipitation falls as snow, and warm, dry summers characterized by a distinct period of water deficit (Major, 1977; Stephenson, 1988).

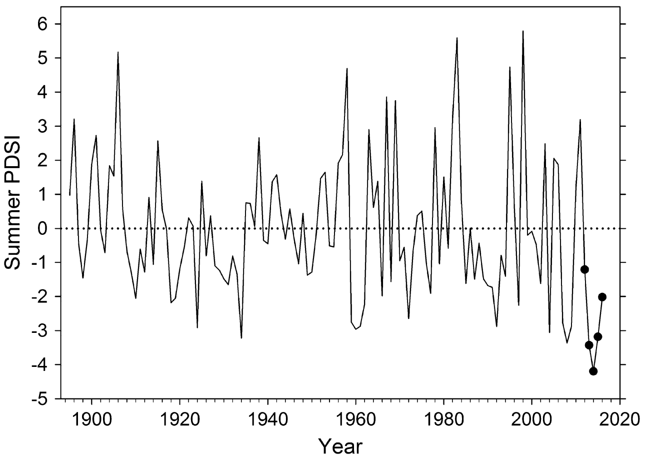

Fig. 1. Re-standardized, self-calibrated summer (June-August) Palmer Drought Severity Index (PDSI) from 1895 to 2016 for the study region. More negative values indicate more severe drought. The five black dots highlight each of the 2012–2016 drought years; 2013 and 2014 are, respectively, the second and first most severe years in the 122-year record.

To characterize historical droughts in our study area, we followed the methods of Williams et al. (2015) to calculate the self-calibrated Palmer Drought Severity Index (PDSI) for a 236,600-ha quadrilateral – ranging from 210 m to 3820 m elevation (mean ~1700 m) – that encompassed all sequoia groves within Sequoia and Kings Canyon national parks. We calculated summer PDSI (June through August) for 1895–2016, using precipitation data from the NOAA ClimGrid dataset (Vose et al., 2014) and temperature data from TopoWx (Oyler et al., 2015), which corrects for known biases in high-elevation temperature records. For years that lacked TopoWx temperature data (i.e., preceding 1948) we used NOAA ClimGrid temperature. Potential evapotranspiration was calculated using the Penman-Monteith approach, with wind speed, humidity, and solar radiation data inputs as described in Williams et al. (2015). As in Williams et al. (2015), our summer PDSI metric was standardized to have a standard deviation of two during a 1921–2000 baseline period.

2.2. Searching for records of foliage dieback in previous droughts

Evidence of giant sequoia responses to the 1924 and 1934 droughts (Fig. 1) was sought in the superintendent's annual reports archived at Sequoia and Kings Canyon national parks; in a contemporary book on giant sequoia natural history (Fry and White, 1930); and in the *Sequoia Nature News Notes* (also called *Sequoia Nature Guide Series*), which comprise ~50 natural history bulletins produced from 1922 to 1937 by Walter Fry (an ardent student of giant sequoias who spent more than 40 years in Sequoia National Park and vicinity). Evidence of sequoia responses to the 1959–1962 drought was sought in the superintendent's monthly reports archived at Sequoia and Kings Canyon national parks. Finally, any sequoia responses to drought from the 1970 s to the present would fall within the memories of some local foresters we consulted, and one of us (NLS) has worked among the sequoias most years since

Table 1
Characteristics of the eight giant sequoia groves in which foliage dieback surveys were conducted in both 2014 and 2015.

Grove characteristics				Approximate area surveyed (ha)		Number of sequoias surveyed		Mean% foliage dieback	
Grove name	UTM coordinates (zone 11, NAD 83)	Mean elev. (m)	Size (ha)	2014	2015	2014	2015	2014	2015
Atwell	4037020 N, 349210 E	2201	542	32.3	27.1	123	118	24.3	7.0
Muir	4055630 N, 335360 E	1986	154	9.1	9.2	50	38	23.7	11.8
East Fork	4035110 N, 351110 E	2008	397	42.1	43.5	131	156	20.5	6.8
Garfield	4022500 N, 345930 E	2001	624	74.1	69.3	293	272	19.2	6.8
Lost	4057740 N, 336600 E	2028	21	7.4	7.6	49	38	19.1	7.6
Giant Forest	4048090 N, 342780 E	2058	935	441.5	444.3	2176	2241	13.5	6.8
Redwood Mountain	4060460 N, 332240 E	1850	1185	193.1	197.6	1283	1230	13.1	7.5
Grant	4068750 N, 323490 E	1883	85	47.7	40.3	173	155	6.8	7.5