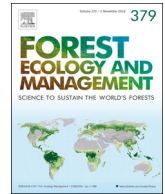




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# Tree mortality following drought in the central and southern Sierra Nevada, California, U.S. <sup>☆</sup>



Christopher J. Fettig<sup>a,\*</sup>, Leif A. Mortenson<sup>b</sup>, Beverly M. Bulaon<sup>c</sup>, Patra B. Foulk<sup>d</sup>

<sup>a</sup> Pacific Southwest Research Station, USDA Forest Service, 1731 Research Park Drive, Davis, CA 95618, USA

<sup>b</sup> Pacific Southwest Research Station, USDA Forest Service, 2480 Carson Road, Placerville, CA 95667, USA

<sup>c</sup> Forest Health Protection, USDA Forest Service, 19777 Greenley Road, Sonora, CA 95370, USA

<sup>d</sup> Eldorado National Forest, USDA Forest Service, 4260 Eight Mile Road, Camino, CA 95709, USA

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## ABSTRACT

Much of California, U.S. experienced a severe drought in 2012–2015 inciting a large tree mortality event in the central and southern Sierra Nevada. We assessed causal agents and rates of tree mortality, and short-term impacts to forest structure and composition based on a network of 11.3-m fixed-radius plots installed within three elevation bands on the Eldorado, Stanislaus, Sierra and Sequoia National Forests (914–1219, 1219–1524 and 1524–1829 m on the Eldorado, Stanislaus, Sierra; 1219–1524, 1524–1829, and 1829–2134 m on the Sequoia), where tree mortality was most severe. About 48.9% of trees died between 2014 and 2017. Tree mortality ranged from  $46.1 \pm 3.3\%$  on the Eldorado National Forest to  $58.7 \pm 3.7\%$  on the Sierra National Forest. Significantly higher levels of tree mortality occurred in the low elevation band ( $60.4 \pm 3.0\%$ ) compared to the high elevation band ( $46.1 \pm 2.9\%$ ). Ponderosa pine, *Pinus ponderosa* Dougl. ex Laws., exhibited the highest levels of tree mortality (89.6%), with 39.4% of plots losing all *P. ponderosa*. Mortality of *P. ponderosa* was highest at the lowest elevations, concentrated in larger-diameter trees, and attributed primarily to colonization by western pine beetle, *Dendroctonus brevicomis* LeConte. About 89% of *P. ponderosa* in the three largest diameter classes were killed, representing loss of an important structural component of these forests with implications to wildlife species of conservation concern. Sugar pine, *P. lambertiana* Dougl., exhibited the second highest levels of tree mortality (48.1%). Mortality of *P. lambertiana* was concentrated in the mid-diameter classes and attributed primarily to colonization by mountain pine beetle, *D. ponderosae* Hopkins. White fir, *Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr., and incense cedar, *Calocedrus decurrens* (Torr.) Florin, exhibited 26.3% and 23.2% mortality, respectively. Only one *Quercus* died. Tree mortality (numbers of trees killed) was positively correlated with tree density and slope. A time lag was observed between the occurrence of drought and the majority of tree mortality. Tree regeneration (seedlings and saplings) was dominated by *C. decurrens* and *Quercus* spp., representing a potential long-term shift in composition from forests that were dominated by *P. ponderosa*. About 22.2% of plots contained plant species considered invasive, including cheatgrass, *Bromus tectorum* L., ripgut brome, *Bromus diandrus* Roth, bull thistle, *Cirsium vulgare* (Savi) Ten., and yellow star-thistle, *Centaurea solstitialis* L. The implications of these and other results to recovery and management of drought-impacted forests in the central and southern Sierra Nevada are discussed.

## 1. Introduction

Much of the western slope of the Sierra Nevada experiences a “Mediterranean-type climate”, indicative of an annual dry period characterized by hot, dry summers followed by an annual wet period characterized by cool, moist winters. While droughts have had an important influence on this region for millennia (Cook et al., 2007), the

most recent drought (2012–2015) was characterized by large precipitation deficits and abnormally high temperatures during both the wet and dry seasons (Aghakouchak et al., 2014; Williams et al., 2015), and in some areas is thought to be the most severe in 1200 years (Griffin and Anchukaitis, 2014). In particular, 2014 is noted for the lowest Palmer Drought Severity Index recorded for 1895–2017, when instrumental records were widely available ([www.ncdc.noaa.gov/cag/](http://www.ncdc.noaa.gov/cag/)). The

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\* Corresponding author.

E-mail address: [cfettig@fs.fed.us](mailto:cfettig@fs.fed.us) (C.J. Fettig).

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2012–2015 drought resulted in progressive canopy water stress of at least 888 million trees and severe canopy water stress of at least 58 million trees (Asner et al., 2016), substantial mortality of dominant and co-dominant trees (Brodrick and Asner, 2017), and impacts to many ecological goods and services. The level of tree mortality observed is considered by some to be unprecedented (Stephens et al., 2018), and over time will influence the frequency and severity of other disturbances. For example, Stephens et al. (2018) concluded that a greater potential for “mass fires” exists in future decades driven by the amount, size and continuity of dry combustible woody fuels, which could produce large, severe and uncontrollable wildfires.

In 2015, the USDA Forest Service Aerial Detection Survey (ADS), the group responsible for conducting annually surveys of insect and disease conditions, first reported extensive tree mortality in the central and southern Sierra Nevada, and estimated 29 million trees died in California due to drought and outbreaks of native bark beetles. Winter 2015–2016 brought near normal precipitation to much of central and northern California, but drought stress remained high in many areas of the central and southern Sierra Nevada (U.S. Drought Monitor-California, 3 May 2016, extreme and exceptional categories; <http://droughtmonitor.unl.edu>). ADS estimated an additional 62 million trees died in 2016 and 27 million trees in 2017, bringing the total to at least 129 million trees since 2010 (California Department of Forestry and Fire Protection, 2018) (Fig. 1). Much of the mortality occurred in and around the wildland urban interface, putting significant infrastructure and lives at risk (California Tree Mortality Task Force, 2018).

While ~200 species of bark beetles are native to California only a handful is capable of causing tree mortality (Fettig, 2016). Trees of all species, ages and size classes may be colonized and killed, but each bark beetle species exhibits unique host preferences, life history traits, and impacts. In most cases, the resultant tree mortality goes unnoticed until an outbreak occurs, which generally requires several years of favorable weather conducive to beetle survival and population growth, and an abundance of susceptible hosts (Bentz et al., 2010). In particular, drought is an important factor inciting outbreaks of several notable species, including fir engraver, *Scolytus ventralis* LeConte, Jeffrey pine beetle, *Dendroctonus jeffreyi* Hopkins, mountain pine beetle, *D. ponderosae* Hopkins, western pine beetle, *D. brevicomis* LeConte, and several engraver beetles, *Ips* spp. A recent synthesis reported a non-linear relationship between drought intensity and outbreaks of aggressive bark beetles (i.e., those species capable of causing extensive levels of tree mortality) where moderate drought reduces bark beetle population performance and subsequent tree mortality, and severe drought increases bark beetle performance and tree mortality (Kolb et al., 2016).

The primary objective of our research was to determine causes and rates of tree mortality within three elevation bands on the Eldorado, Stanislaus, Sierra and Sequoia National Forests (Fig. 2), and to describe short-term impacts to forest structure and composition. These national



Fig. 1. Tree mortality on the Sequoia National Forest, California, U.S., 12 April 2017. (Photo: C. Fettig, USDA Forest Service).

forests are the four most southerly on the western slope of the Sierra Nevada, and experienced the highest levels of tree mortality (California Department of Forestry and Fire Protection, 2018). Herein, we concentrate on impacts to tree size, density and species diversity, and provide baseline data on tree regeneration and invasive weeds. The network of plots created provides opportunities for monitoring other changes over time (e.g., fuels and snag demography).

## 2. Materials and methods

### 2.1. Study area and plot selection

A network of 180 11.3-m fixed-radius plots (0.041-ha) was established on the Eldorado, Stanislaus, Sierra and Sequoia National Forests, California, 2016–2017 (Fig. 2). Fifteen plots (three groups of five plots) were distributed in each of three elevation bands on each national forest: 914–1219 m, 1219–1524 m and 1524–1829 m on the Eldorado, Stanislaus, and Sierra, and 1219–1524 m, 1524–1829 m, and 1829–2134 m on the Sequoia. The Sequoia National Forest is the most southerly in our network, and ponderosa pine, *Pinus ponderosa* Dougl. ex. Laws., seldom grows there below ~1524 m elevation, which explains the increase in elevation bands. Individual plots ranged from 929 m elevation on the Georgetown Ranger District, Eldorado National Forest (UTM: 10S 693967 4307517) to 2006 m elevation on the Western Divide Ranger District, Sequoia National Forest (UTM: 11S 358511 3988017). For inclusion in the network, plots were required to be  $\geq 35\%$  *P. ponderosa* by basal area, to contain  $\geq 10\%$  *P. ponderosa* mortality in the last two years (as determined by presence of crown fade, Section 2.2), and unburned in the last decade. Plots meeting these criteria were randomly selected within groups, but separated by  $\geq 100$  m. Groups within elevation bands were separated by  $> 1.6$  km.

### 2.2. Data collection and analyses

On each plot, trees  $\geq 6.35$  cm dbh (diameter at breast height, 1.37 m in height) were numbered, geo-referenced to plot center, and the species, dbh, condition (live or dead, based on the presence or absence of crown fade), cause of death (if applicable), and year of death (if applicable) were recorded. For trees that died prior to plot establishment, year of death was estimated based on the color of faded needles in the crown and degree of needle retention (i.e., 1 year prior,  $> 90\%$  retention of yellow and/or red needles; 2 years prior,  $\geq 50\text{--}90\%$  retention of red needles;  $\geq 3$  years prior,  $< 50\%$  retention of red and/or gray needles) (Miller and Keen, 1960; Fettig et al., 2008). Very few trees ( $< 50$ , across the network) died  $\geq 3$  years prior to plot establishment, and were ignored. For trees that died after plot establishment, year of death was recorded as the year before crown fade was observed (e.g., in 2016 for trees colonized by bark beetles that year, but that first exhibited crown fade in early 2017). Each plot was surveyed once annually, usually in April–June.

For dead trees, a section of bark  $\sim 625$  cm<sup>2</sup> was removed with a hatchet at  $\sim 2$  m in height on the north and south aspects to determine if bark beetle galleries were present. The shape, distribution and orientation of galleries are commonly used to distinguish among bark beetle species (Furniss and Carolin, 1977). In some cases, deceased bark beetles were present beneath the bark to supplement identifications based on gallery formation. The precise role of each bark beetle species in contributing to tree mortality is generally unknown. In some cases (e.g., *D. brevicomis*), trees must have enough green phloem for successful colonization and brood production to occur (Miller and Keen, 1960). In other cases (e.g., *Ips* and *Scolytus*), successful brood production may also occur in dead and dying trees (Furniss and Carolin, 1977). We attributed tree mortality to colonization by *D. brevicomis*, *D. ponderosae*, California fivespined ips, *Ips paraconfusus* Lanier, pine engraver, *I. pini* (Say), *S. ventralis*, and cedar bark beetles, *Phloeosinus* spp., only when parental and brood galleries were observed in or beneath the

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