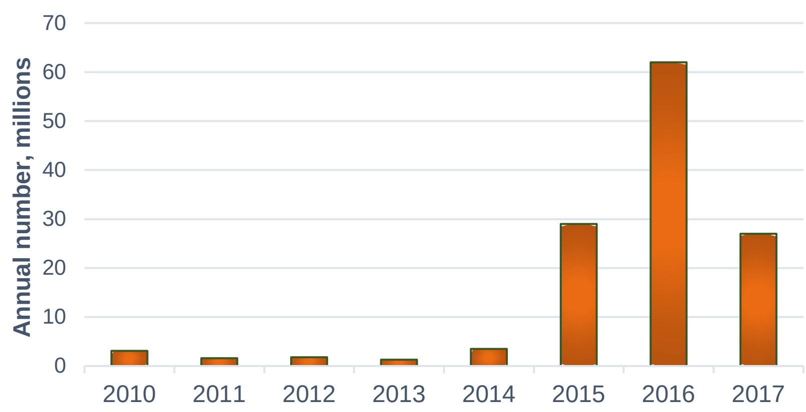
## FOREST TREE MORTALITY

*Since the 2012-2016 drought — the most severe since instrumental records began — tree deaths in forest lands in California increased dramatically. Annual tree mortality was elevated beginning in 2014 and a cumulative total of 129 million trees in forest lands died between 2012 and December 2017. Most of these trees were stressed from higher temperatures and decreasing water availability, making them more vulnerable to insects and pathogens.*

**Figure 1. Estimated number of dead trees (Based on aerial detection surveys)**




Source: Tree Mortality Task Force (based on USFS data), 2017

### *What does the indicator show?*

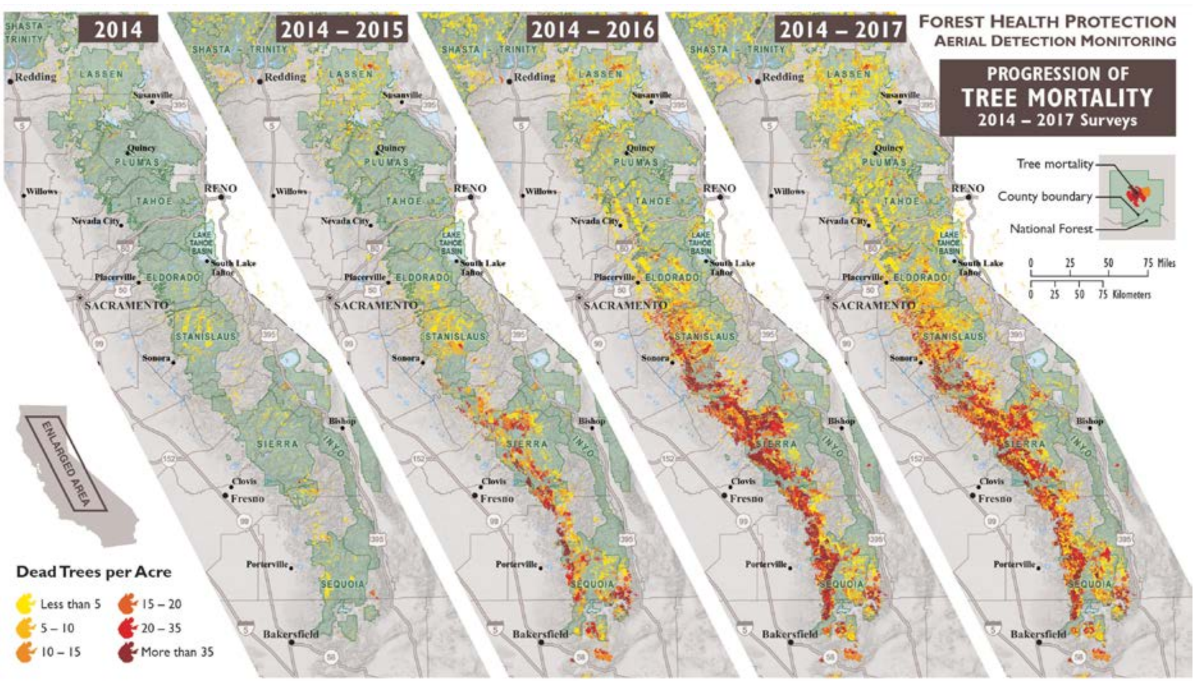
Annual tree mortality in California forests increased in 2014, two years into the 2012-2016 drought, followed by steep increases in 2015 and 2016. Tree deaths in 2017 were also considerably above levels at the beginning of the decade. Figure 1 shows the estimated annual number of dead trees in California forests killed by a variety of agents (not limited to drought or drought-related insect activity), as measured by US Forest Service aerial detection surveys. The largest number of tree deaths in any one year (62 million) was recorded in 2016. The cumulative number of dead trees in forested areas between 2012 and 2017 was an estimated 129 million (USFS, 2017a).

Based on the aerial detection surveys, the maps in Figure 2 show the progression of tree mortality in California's Sierra Nevada Mountains in recent years. The spatial extent and severity of tree mortality have increased since 2014, as the drought in California progressed (USFS, 2017a).

### *Why is this indicator important?*

Forests occupy almost one-third of California and are a vital resource for the state, providing important ecosystem services including water provision, air purification, carbon sequestration, and recreational opportunities (CNRA, 2016). Accelerating tree mortality and the increasing frequency of large-scale high mortality events (known as forest dieback) could have profound effects on these processes. Additionally, there is a potential that increased tree mortality will amplify other climate change-related phenomena such as forest type conversion (a change in tree species or group of species present, for example, from conifers to hardwood; see *Changes in forests and woodlands* indicator) and increased fire risk (see *Wildfires* indicator).

**Figure 2. Maps showing progression of tree mortality**




Source: USFS, 2017

The majority of the trees that have died in California forests are conifers; the majority of deaths involved trees weakened by the drought succumbing to beetle outbreaks (rather than direct physiological stress from the drought) (Moore et al., 2016). Using tree ring data, researchers estimated 2014 to be the worst single drought year in at least the last 1,200 years in the state, as seen in the tree rings of blue oak (*Quercus douglasii*) — the result of unusually low (yet not unprecedented) precipitation and record high temperatures (Griffin and Anchukaitis, 2014). California's pattern of tree mortality corresponds with global trends: increasing tree mortality has been documented on all vegetated continents and in most bioregions over the past two decades and is linked to increasingly dry and hot climatic conditions (Allen et al., 2010).

If forest tree mortality continues at the current elevated rates, it could lead to changes in the species comprising the state's forest ecosystems, conversion of forests to vegetation types with less trees, or even the outright loss of forests (Kobe, 1996; Lenihan et al., 2003; Thorne et al., 2008; Millar et al., 2015).

Recognizing the unprecedented extent of the recent tree mortality, Governor Brown proclaimed a state of emergency in October 2015 to address its impacts to communities in the affected regions (Brown, 2015). Among other things, the proclamation directs state agencies to take action to minimize the risks to public safety associated with the large number of dead trees, and to address the increased threat of wildfires and erosion in the affected areas.

***What factors influence this indicator?***

Tree mortality is a complex process that often involves a chain of events and a wide range of factors, often making it difficult to assign a single ultimate cause of death. In fact, many of the disturbances contributing to tree mortality are overlapping and integrative events that may play a role in observed large stand-level forest dieback and changes in the composition of forest trees and their structure, and shifts in tree species ranges in the western United States (Clark et al., 2016).

Regional warming and the consequent drought stress were found to be the most likely drivers of increased background tree mortality in old growth western forests; the observed regional warming from the 1970s to 2000s contributed to hydrologic changes — less precipitation falling as snow, declining snowpack water content, earlier spring snowmelt and runoff, and a lengthening of the summer drought (van Mantgem et al., 2009). The 2012-2016 drought occurred at a time of record warmth — 2014 is the warmest year on record, followed by 2015 — accompanied by record low snowpack (DWR, 2017) (also see *Drought* indicator).

Climatic water deficit (CWD) is used as a measure of water stress experienced by plants (Stephenson, 1998). CWD can be thought of as the amount of additional water that would have evaporated or been transpired by plants had it been present in the soils; it integrates plant water demand relative to soil moisture availability. Increases in CWD are associated with a warming climate, as warmer air temperatures increase plant water demand for evapotranspiration (Flint et al., 2013; Thorne et al., 2015); reduced precipitation and earlier snowmelt also contribute to a higher CWD by decreasing available water. Under increased CWD conditions, trees could lose their ability to convey water from root to leaf via a tree's xylem — a mechanism that has been shown to lead to drought-induced tree mortality (Adams et al., 2010). The tree mortality during the drought correlated with increases in CWD (Young et al., 2017).

The frequency, severity, and extent of large forest dieback events, such as the one discussed here, are of concern. The most recent drought in California may foreshadow an increasingly common condition in which warm temperatures coincide with periodically occurring dry years — "hotter drought" — contributing to increasing physiological stress in trees (Young et al., 2017; Diffenbaugh et al., 2015). In fact, rising global temperatures have contributed to droughts of a severity that is unprecedented in the last century or more (Millar et al., 2015).

Competition for resources is also a factor. Most of California's coniferous forests have more trees now than 100 years ago, a consequence of fire suppression (Stephens et al., 2018). Tree mortality increased disproportionately in areas that were both dry and dense (Young et al., 2017).

Another effect of warming temperatures is the enhanced growth and reproduction of insects and pathogens that attack trees (van Mantgem et al., 2009). In recent decades, the outbreaks of insects and pathogens have resulted in extensive forest defoliation, canopy dieback, declines in growth, and forest mortality in western North America. Some widespread dieback events have occurred concomitant with infestation outbreaks where the insect populations increased due to warmer winter temperatures (Bentz et al., 2010); in California, however, the effect of warmer winter temperatures on insect populations has not been demonstrated. In many regions, drought and unusually warm temperatures have weakened trees and accelerated the bark beetle population growth (Adams et al., 2010). Temperature-driven insect population increases in combination with water deficit can have disproportionate consequences on tree mortality than would have occurred due to drought or insects alone (Anderegg, 2015).

### *Technical Considerations*

Data Characteristics

The aerial tree mortality surveys are based on annual small plane reconnaissance over California's forested lands. Forested areas are mapped on a one-acre basis, and the following recorded: (a) damage type, (b) number of trees affected, and (c) affected tree species. Generally, areas with <1 tree per acre of mortality are considered to have "background" or "normal" levels of mortality and are not usually mapped during the flight. If low levels of mortality are indicative of a localized pest-related event, the areas are supposed to be mapped; however, it is usually not possible to systematically discern the cause of such low-level mortality using visual aerial surveys.

Lands dominated by hardwood and conifer tree species are considered forest lands in California. Affected tree species are recorded to species level if possible (Sugar Pine and White Fir), or to genus level (pine, fir). In areas where two or more tree species are affected, the surveyor will designate the proportion of damage affecting each species (e.g., 25 percent Sugar Pine, 75 percent White Fir), or preferably, an estimate of trees per acre for each species affected is recorded. Lands characterized as urban, orchards, and windbreaks are not mapped. Tree injuries that are recorded are typically defoliation, discoloration, dieback or more commonly death. Survey results provide a reasonable estimate of dead trees that aid in the understanding of the mortality event (USFS, 2017b). It is possible there is some level of error in the density estimates. However, over large areas covered, the results will show the correct trends.

Strengths and Limitations of the Data

Aerial surveys cannot detect mortality until the trees have been dead some months and the foliage has dried out and faded from green to a red or yellow color. Thus, currently infested, but dead, trees still look healthy from a distance but may not be counted in the aerial survey.

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