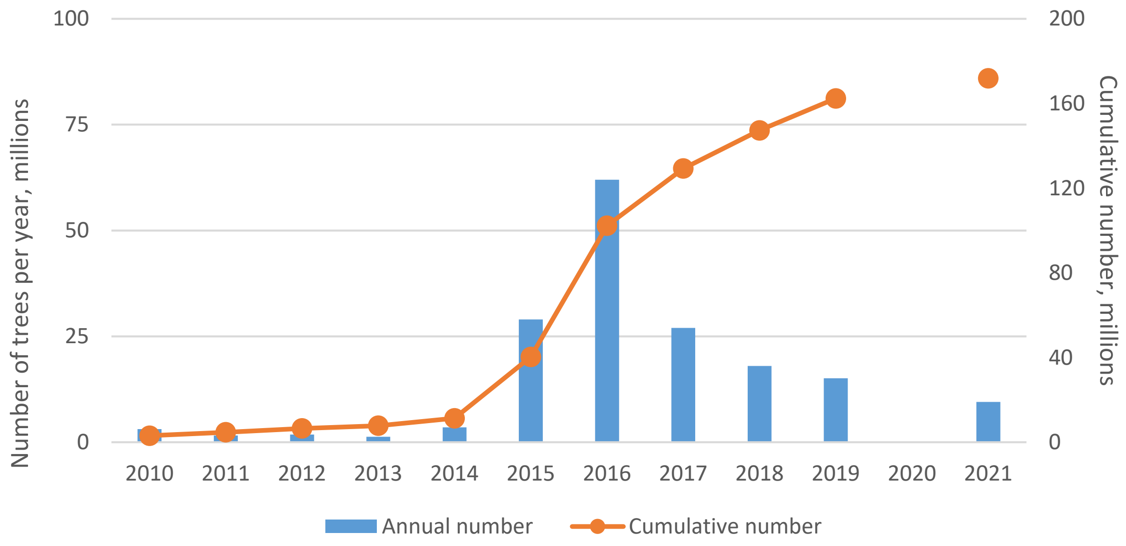
FOREST TREE MORTALITY

Since the 2012-2016 drought — California's most severe since instrumental records began — tree deaths in California forest lands increased dramatically. An estimated 170 million trees in forest lands died between 2010 and 2021. Most of these trees were stressed from higher temperatures and decreased water availability, making them more vulnerable to insects and pathogens.

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



Source: USFS, 2020a and b, 2021a

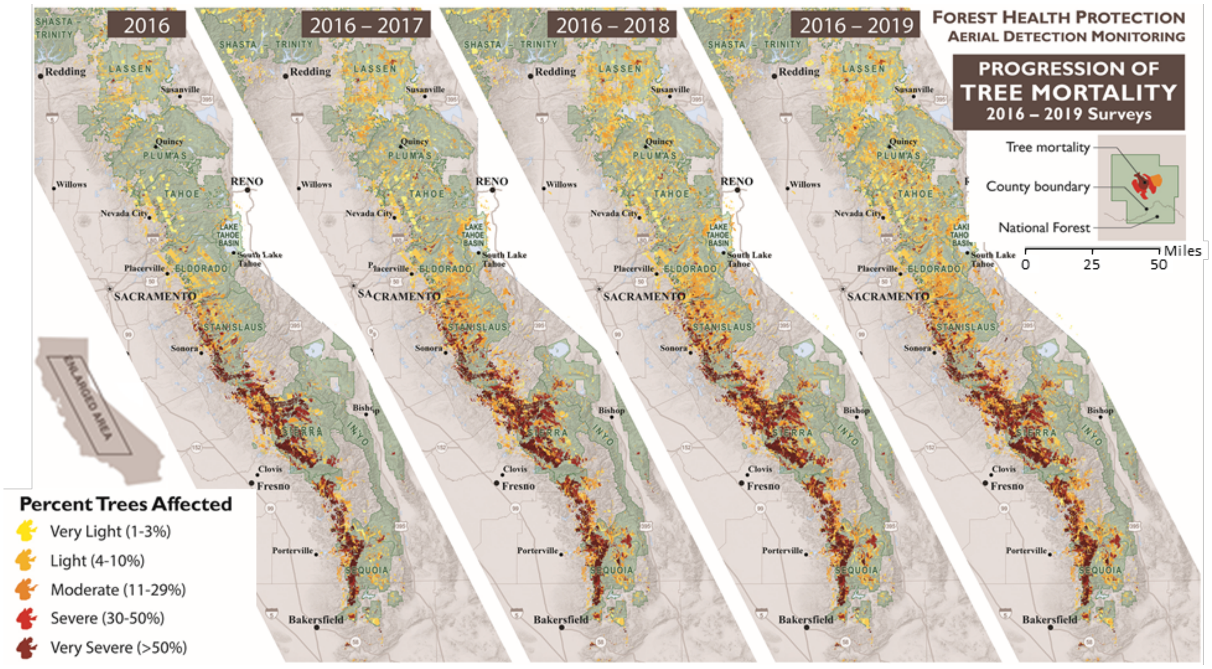
**Aerial surveys were suspended in 2020 due to COVID-19 pandemic. Estimate for 2021 is based on slightly different methodology and is not directly comparable to prior years.*

What does the indicator show?

Figure 1 shows the estimated annual number of dead trees in California forests, based on US Forest Service Aerial Detection Surveys (ADS). The estimates include trees killed by a variety of agents including drought and drought-related insect activity, but not wildfire. Annual tree mortality in California forests showed a steep increase in 2015 (USFS, 2016), as the 2012-2016 drought progressed. The largest number of tree deaths in any one year (62 million, more than double the previous year's estimate) was recorded in 2016, the fourth year of the drought. Relatively wet water years (October – September) followed in 2017-2018 and 2018-2019. Tree deaths during these years were lower than during the drought, but still six to nine times higher than in the beginning of the decade.

California again entered into drought in 2020. Since ADS were suspended in 2020, however, no estimates are presented for that year. While the methodology used in 2021 differed from, and thus yielded estimates not directly comparable to earlier years', the estimated 9.5 million dead trees suggest a decrease although the mortality rate still remains above pre-2012-2016 drought levels (USFS, 2021d). Figure 1 also shows the cumulative number of dead trees in forested areas between 2010 and 2021 at more than an estimated 170 million (USFS, 2021d and e).

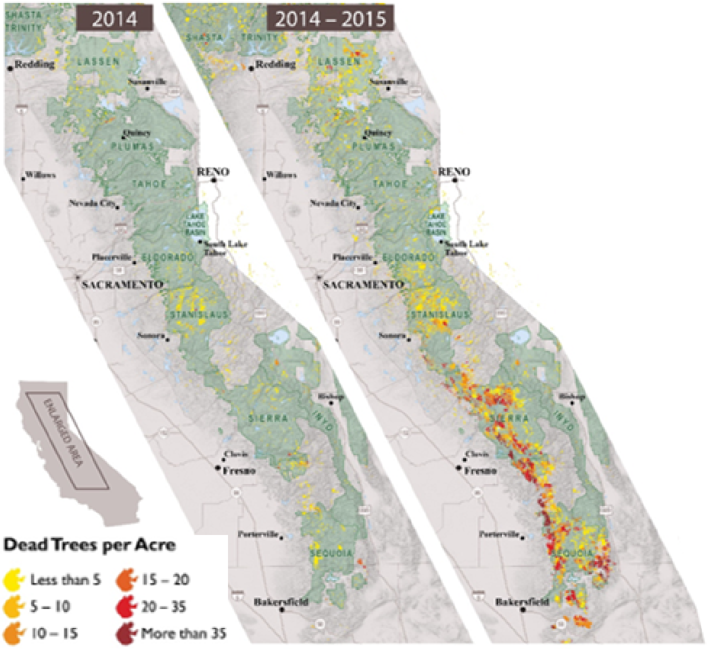
Figure 2. Maps showing progression of tree mortality, 2016 to 2019



Source: USFS, 2021b

The maps in Figure 2 show the progression of cumulative tree mortality between 2016 and 2019 in California's Sierra Nevada Mountains, where mortality has been the most severe. For comparison, Figure 3 shows mortality between 2014 and 2015. The extent and severity of tree mortality increased substantially in 2016, especially in lower elevation forests of the Southern Sierra Nevada where the drought was most severe and prolonged (USFS, 2017). Extensive mortality became evident farther north and into higher elevations beginning in 2016.

Figure 3. Tree mortality in the Sierra Nevada Mountains, 2014 to 2015



Source: Modified from USFS 2021c

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. Tree mortality has been linked to increasingly dry and hot climatic conditions (Allen et al., 2010).

As noted in the Tribal section of this report, many Tribes have noticed an increase in tree mortality. Tribes participating in the Eastern Sierra and Southern California listening sessions including Bishop, Big Pine, Mono Lake Kutzadika'a, Santa Ynez, Pala, Barona, and others have witnessed increased tree mortality of conifers, oaks and pine nut trees. During the Lake, Sonoma and Mendocino listening session, the Middletown Rancheria shared this image of local trees (Figure 4) that are dying or already dead. The Kashia Band of Pomo Indians are also experiencing tree mortality and now refer to these stands or dead and dying trees as "match sticks".

Figure 4. Dead and dying trees at Middletown Rancheria

Photo credit: Mike Shaver, Environmental Director, Middletown Rancheria

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 and air purification, carbon sequestration, building materials, renewable energy, cultural resources, wildlife habitat, and recreational opportunities (CNRA, 2016). Accelerating tree mortality and the increasing frequency of large-scale and high mortality events (known as forest dieback) could have profound effects on these ecosystem services. The loss of large trees, in particular, represents a significant reduction in the capacity of forests to store carbon, further exacerbating climate change.

Additionally, there is evidence that increased tree mortality amplifies 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 wildfire risk (see *Wildfires* indicator). If forest tree mortality levels continue at elevated rates, changes in the species comprising the state's forest ecosystems, conversion of forests to vegetation types with fewer trees, or even the outright loss of forests are anticipated (Larvie et al., 2019; Lenihan et al., 2003; Millar et al., 2015; Thorne et al., 2008). The unprecedented scale of tree mortality and the increased fuel loads present increased risks of large, severe fires in the coming decades (Stephens et al., 2018).

A state of emergency was proclaimed in October 2015 to address the impacts of the unprecedented tree deaths to communities in 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. A state task force developed in response to this emergency order has since evolved to broadly address forest health issues, including tree mortality and increasing wildfire risk. In 2021 the task force released the California Wildfire and Forest Resilience Action Plan, establishing State strategies and identifying key actions for the coming years (FMTF, 2021).

What factors influence this indicator?

Tree mortality is a complex process that often involves a chain of events and a wide range of factors, making it difficult to assign a single cause of death. Various pathogens contributing to tree mortality spatially overlap with drought, wildfire, insects and diseases that in combination result in large stand-level forest dieback, changes in the composition of forest trees, and shifts in tree species ranges in the western United States (Clark et al., 2016).

The death of over 170 million trees over the last decade can be attributed to the combined effects of extreme drought and forest management that suppressed wildfires. Fire suppression practices, which started in the 1930s, resulted in increasing tree densities, as shade-tolerant and fire-sensitive tree species were able to establish (Stephens et al., 2018). California and most of the western United States ecosystems are fire-dependent and fire-adapted; for millennia, periodic fire was critical to maintaining ecosystem integrity. Forest densification has increased competition among trees for water and other resources, leaving them increasingly susceptible to mortality from drought and bark beetles.

The 2012-2016 drought in California may foreshadow an increasingly common condition in which warming temperatures coincide with dry years, creating hotter or more frequent droughts. 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 — the result of unusually low (yet not unprecedented) precipitation and record high temperatures (Griffin and Anchukaitis, 2014). Such hotter droughts increase the physiological stress in trees (Diffenbaugh et al., 2015; Young et al., 2017). In fact, rising global temperatures have contributed to droughts of a severity that is unprecedented in the last century (Millar et al., 2015). Regional warming and drought change the hydrology at landscape scales (Thorne et al. 2015). Less precipitation falling as snow, declining snowpack water content, and earlier spring snowmelt and runoff have impacted old growth western forests (van Mantgem et al., 2009). The 2012-2016 drought occurred at a time of record warmth — 2014 was, at that time, the warmest year on record, followed by 2015 — accompanied by record low snowpack (DWR, 2017) (also see the *Air temperatures, Drought,* and *Snow-water content* indicators).

Large scale, drought-induced tree mortality events also create feedbacks that exacerbate the threat of wildfires (Stephens et al., 2018). Across the west, drier conditions have also amplified the occurrence and extent of wildfires (Abatzoglou and Williams, 2016) that directly kill trees and burn trees that previously died due to other factors. Techniques to assess the overall levels of tree mortality associated with increasingly intense wildfires are emerging (for example, the Monitoring Trends in Burn Severity Program and the Rapid Assessment of Vegetation Condition After Wildfire Program); however, a comprehensive study for California is not yet available. An example of a smaller-area study estimated that about 2,300 to 3,600 giant sequoias (*Sequoiadendron giganteum*) over four feet in diameter were killed or will die in the next three to five years following the 2021 KNP Complex and Windy Fires (Shive et al., 2021). These estimates correspond to approximately 3 to 5 percent of the entire sequoia population in the Sierra Nevada. In the prior year, an estimated 7,500 to 10,600 large sequoias (about 10 to 14 percent of Sierra Nevada population) were lost in the Castle Fire (Stephenson and Brigham, 2021).

Competition for resources is also a factor influencing tree mortality. Most of California’s coniferous forests have higher densities of trees now than 100 years ago, a consequence of fire suppression (McIntyre et al. 2015; Stephens et al., 2018). Denser vegetation increases the demand for water, and tree mortality associated with the drought increased disproportionately in areas that were both dry and dense (Young et al., 2017).

Drying in the deep rooting zone has been closely tied to tree mortality in the Sierra Nevada Forest (Goulden and Bales, 2019). From 2012 to 2015, cumulative evapotranspiration exceeded precipitation by the equivalent of nearly 60 inches of rainfall, and the subsurface moisture was exhausted to depths of 15 to 60 feet. This stress on trees was further intensified due to the higher-than-historical density of trees. The combination of the dense canopy and warm temperatures in the southern Sierra Nevada forests may have increased die-off by 55 percent (Goulden and Bales, 2019).

Tree mortality during the drought correlated with increases in climatic water deficit (CWD) (Young et al., 2017). 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 been transpired by plants had it been present in the soil; it integrates plant water demand relative to soil moisture availability. Increases in CWD are associated with a warming climate, as plant water demand for evapotranspiration increase as temperatures rise (Flint et al., 2013; Thorne et al., 2015). Reduced precipitation and earlier snowmelt also contribute to a higher CWD by decreasing available soil water. Under increased CWD conditions, trees could lose their ability to convey water from root to leaf via a tree's xylem — a direct mechanism that has been shown to lead to drought-induced tree mortality (Adams et al., 2010).

In addition to creating vegetative stress, warming temperatures provide favorable conditions for the growth and reproduction of insects and pathogens, increasing the threat of tree infestations and diseases (van Mantgem et al., 2009). 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). The majority of conifer deaths involved trees weakened by drought succumbing to beetle outbreaks, rather than direct physiological stress from drought (Moore et al., 2016). 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 were concomitant with infestation outbreaks where the insect populations increased due to warmer winter temperatures (Bentz et al., 2010).

Some of the predominant pests and diseases affecting California's forests are:

> **Western pine beetle (*Dendroctonus brevicomis*).** The western pine beetle is one of several native bark beetle species of the western United States. In California's Sierra Nevada, drought and attacks by pine beetles have contributed to large proportions of ponderosa pine mortality (Fettig et al., 2019). Overall, about 49 percent of the trees in the region died between 2014 and 2017. Ponderosa pine and sugar pine were most affected, with 90 and 48 percent mortality, respectively. During the 2012–2015 drought, warmer temperatures increased the bark beetle–induced tree mortality by thirty percent (Robbins et al., 2022). Specifically, the warming increased the maturation rate of the beetles and decreased the beetle's mortality during winter. This led to a larger beetle population during periods when trees were more susceptible due to drought. Large extents of beetle-killed trees have increased the fuel loads for wildfire, which in turn leads to higher levels of additional tree mortality during the fire (Wayman & Safford 2021).
>
> **Sudden oak death (*Phytophthora ramorum).*** In coastal northern California, sudden oak death (SOD) is the most important cause of tree mortality. The SOD organism, an invasive pathogen, was first detected in California around 1990. *P. ramorum* affects a broad host range of over 130 species of trees, shrubs, herbs, and ferns, many of which are moved long distances via the nursery industry (Cobb et al, 2020). The pathogen can kill three of four species that comprise an important part of California's northern coastal forests: tanoak (*Notholithocarpus densiflorus*), coast live oak (*Quercus agrifolia*), and California black oak (*Q. kelloggii*); the fourth

species, California bay laurel (*Umbellularia californica*), is a carrier of the disease. Using a demographic model, Cobb et al. found that SOD has killed at least 48 million trees and infected about 150 million more since 1995, while about 1.8 billion remain at risk. (Cobb et al., 2020). The SOD pathogen benefits from warmer rainy temperatures, and although a direct connection has not been established, historical warming of air temperature in the wet winter months of California's north coast ecoregion has been observed, with mean air temperature warming of 1.33 +/- 0.29°F from 1951-1980 (33.63°F) to 1981-2020 (34.95°F) (Flint et al. 2021, analysis by Thorne, personal communication).

Shot Hole Borers (*Euwallacea* spp.). Some urban and natural forests in southern California have been severely affected by beetle-related tree mortality. Two beetle species of Invasive Shot Hole Borers (ISHB) introduce a fungus that causes Fusarium dieback (FD) that can infect 137 species of trees (UCANR, 2021). ISHB-FD has killed thousands of trees in Southern California, and can impact riparian, agricultural and urban tree species (Boland 2018; Eskalen et al., 2018). ISHB-FD has also moved into riparian systems in Southern California, including the Tijuana River and the Santa Clara River riparian forests (Bennett, 2020).

Goldspotted Oak Borer (*Agrilus auroguttatus*). Also in Southern California, a beetle called the Goldspotted Oak Borer, is a serious threat that was introduced from Arizona. It can kill a range of oak species in California, including coast live oak and black oak (Coleman et al., 2017). In the highly infested area of eastern San Diego County, oak mortality levels have approached 45 percent (Coleman et al., 2017). The beetle is killing trees on federal, state, private, and local Native American lands in many areas of San Diego County (University of California Cooperative Extension, 2021). The Iipay Nation of Santa Ysabel and the Barona Band of Mission Indians have reported the death of oak trees on their reservations, located in San Diego County (PBMI and SYBCI, 2021). The 2021 ADS detected 19,000 dead trees on 4,000 acres in the same area (USFS, 2021e).

Climate change, however, may not always worsen diseases or pathogens. A recent study found that favorable climate conditions for a pathogen, white pine blister rust (WPBR; *Cronartium ribicola*), had shifted to higher elevations over 20 years, due to the hotter and drier climate (Dudney et al., 2021). The pathogen attacks five-needle pines, or white pines, and is considered a cool-weather disease. While the estimated range of the pathogen expanded in the colder, higher elevation areas of Sequoia and Kings Canyon National Parks (by 780 km^2), its actual observed presence decreased by 33 percent between the 1996 and 2016 surveys. One explanation begins with the fact that WPBR depends on the host (a white pine species) and an alternate host (plants and shrubs from the genera *Ribes*, *Castellja* and *Pedicularis*). Because of the drought, there were fewer of the alternate host species, and that may have suppressed the spread of the pathogen. However, there is concern that several species of white pine that inhabit high-elevation subalpine conditions may now be exposed to this pathogen.

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 are 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.

For the aerial surveys, lands dominated by hardwood and conifer tree species are considered forest lands. Affected tree 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, 2019b). There will be some level of error in the density estimates, however, over large areas, the results should 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 alive trees that still look healthy from a distance may not be counted in the aerial survey. Unfortunately, the aerial detection survey program was suspended in 2020 due to the COVID 19 pandemic. The 2021 ADS did not include all areas covered by past aerial survey operations; instead remote sensing was used to analyze some of the areas. Thus, after 2019, tree mortality data comparable to earlier years are not available to assess the impacts of next wave of drought that began in 2020.

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