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Synthesis of Research into the Long-Term Outlook for Sierra Nevada Forests following the Current Bark Beetle Epidemic¹

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Abstract

This paper summarizes the 2012-2017 bark beetle epidemic in the Sierra Nevada and its implications for long-term changes in tree species composition and forest structure. Preliminary plot and landscape-scale data are reviewed, showing higher levels of mortality for pine species and greater impacts in the southern Sierra Nevada compared to the northern portions of the range. The federal government owns approximately three quarters of the forested area impacted by high levels of tree mortality, with the remainder of the land controlled by nonindustrial (18%) and industrial (6%) ownerships. The accumulation of dead and downed fuel and standing dead trees is expected to increase fire intensity and severity, and pose significant hazards for fire control efforts.

Potential long-term changes in Sierra Nevada forest composition were explored with a GIS analysis conducted for the Sierra National Forest, located in the southern Sierra. GIS layers included very high fire threat, aspect, high tree mortality, topographic position classification, and climatic exposure. A factor of one was assigned to each parameter (i.e., no weighting for any of the variables). The modeling showed that 4% of the Sierra National Forest is at very high risk for type conversion from mixed conifer to shrublands, and 12% is at high risk. This information can inform landowners regarding the general locations where successful reforestation will be most challenging, as well as illustrate the scale of concern for one national forest in the southern Sierra Nevada.

Changes to disturbance regimes, continuing land use changes, and climate change with associated species shifts pose significant challenges for maintaining healthy and resilient forests in the Sierra Nevada. Significant unknowns exist regarding the future species composition for vast portions of this region, but type conversions from mixed conifer to shrublands or oak/grass/woodland appear likely for some areas. Recommended best management practices focus on reducing tree densities, achieving successful reforestation, and using adaptive management in the face of currently unknown future changes in growing conditions. With the exception of the bark beetle epidemic in southern California in the early 2000s, lessons learned from other locations in western North America that have had sustained bark beetle epidemics in the past decade are not directly applicable to Sierra Nevada, with its Mediterranean climate, complex topography, and mixed-conifer forests. For these reasons, ongoing research efforts to characterize and understand tree mortality drivers and changes in forest structure and composition in the Sierra Nevada are extremely important.

Introduction

The recent drought (2012–2015) in California was characterized by large precipitation deficits, abnormally high temperatures, and an unusually severe bark beetle epidemic. While consecutive years of drought are not uncommon in California, this event was the most severe drought in some locations in the last 1,200 years (Griffin and Anchukaitis 2014), and may foreshadow future impacts of drought and associated bark beetle epidemics within the state. Here, we provide a brief summary of bark beetle epidemics in the western part of North America, and our current understanding of the long-term outlook and recovery of forests in the Sierra Nevada, particularly in terms of potential changes in tree species composition and forest structure.

Disturbance in California

While the scale of the current bark beetle epidemic in the Sierra Nevada is unprecedented in recorded history, with 147 million dead trees since 2010 (CAL FIRE and USFS 2019), disturbance is a natural part of forest ecosystems. Disturbance categories can be described by type (e.g., fire, insect epidemic); severity (low, moderate, high); spatial and temporal characteristics (stand level vs landscape level, short-term vs long-term); and disturbance interactions (e.g., drought leading to insect epidemic). The current epidemic can be characterized as a high-severity, drought-induced insect epidemic at the landscape scale with long-term implications, and is representative of a new era of “mega-disturbances” – sudden tree mortality events greater than have been recorded in human history (Allen et al. 2015, Millar and Stephenson 2015). Mega-disturbances in California include both catastrophic wildfires and large-scale bark beetle epidemics (Stephens et al. 2014, Axelson 2017).

Over the period of 1984 to 2012, tree mortality in California was greater due to wildfire than bark beetles, in contrast to most other western states, owing to our lower elevation and drier forests (Hicke et al. 2016). However, it is likely that this trend has reversed with the current bark beetle epidemic. Several native species of bark beetles occur in California, and can be characterized as being host and host size specific (Fettig 2016). Under normal circumstances, bark beetle infestations act as a natural thinning agent, since they generally result in stands where only some of the trees are killed. Tree preferences for western pine beetle include ponderosa and Coulter pine (>16 inch diameter). Mountain pine beetles attack many pine species, and prefer mid-sized trees, while *Ips* species impact most pine species and prefer smaller trees or the tops of larger trees. Fir engraver beetles attack and kill true fir trees of any size, including white and red fir (true firs) in the Sierra Nevada. Western and mountain pine beetles were the dominant species impacting Sierra Nevada conifers in the 2012-2017 epidemic, primarily affecting ponderosa and sugar pine at lower elevations. In 2017, fir engraver beetles were the dominant agent of tree mortality, impacting true fir species (USFS 2017a, Figure 1).

For the Sierra Nevada, fire exclusion since the early 1900s has caused pine seedling density to significantly decrease, with large density increases for shade tolerant species such as incense cedar and white fir. Historical photos illustrate that Sierra Nevada mixed-conifer forests were highly clustered with gaps and overall low stand density (Lydersen et al. 2013). Currently, mixed-conifer stands have much higher densities dominated by smaller, shade-tolerant tree species (Smith 2007, Butsic et al. 2017, Safford and Stevens 2017). In California, strong relationships between stand density and bark beetle impacts have been revealed, where denser stands have experienced much greater levels of tree mortality than those with lower densities (Hayes et al. 2009).

Current Tree Mortality

Data are being collected by various researchers and institutions to reveal landscape and stand level impacts from the current bark beetle epidemic. At the landscape level,

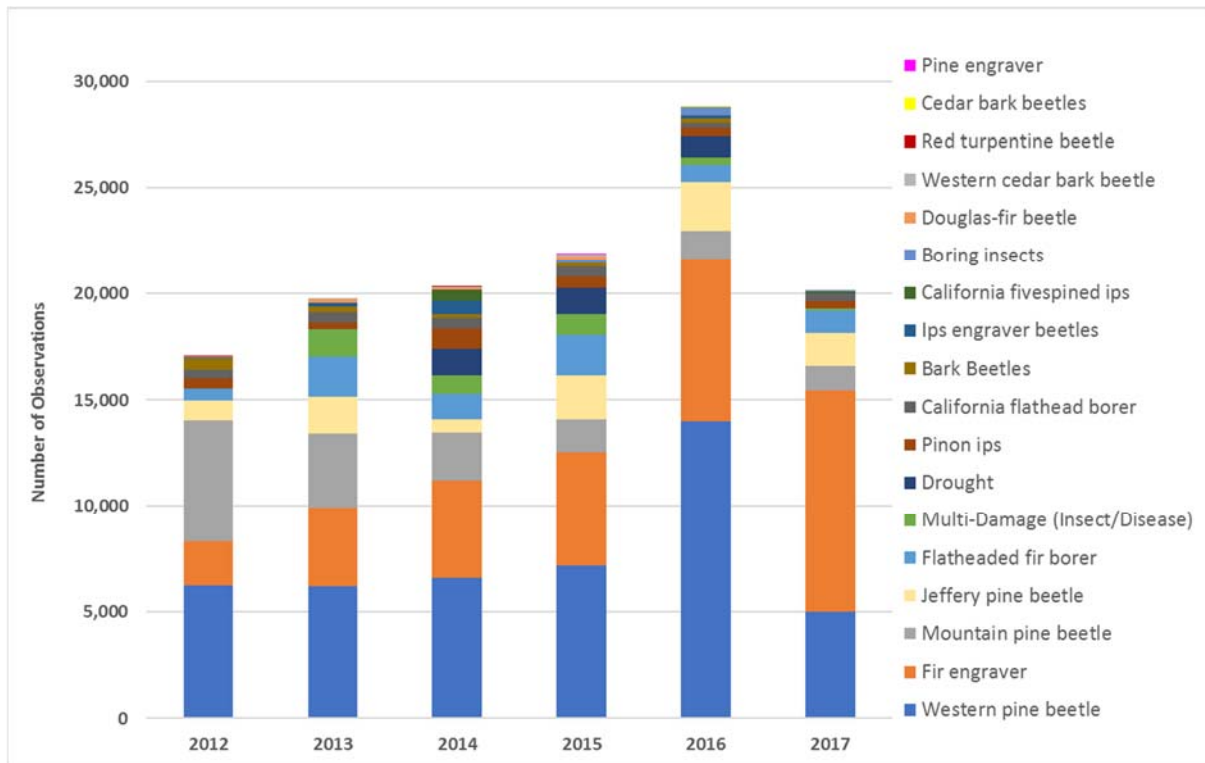


Figure 1. Aerial Detection Survey damage causing agents, 2012–2017. (USFS Region 5 Aerial Detection Survey).

satellite image mapping by Potter (2017) found that the highest tree mortality was located in the Sierra and Sequoia national forests, and that since 2013, over 50% of mortality occurred in the mid-elevation zone of approximately 3,200 feet to 6,500 feet. Brodrick and Asner (2017) described how remotely-sensed data on sustained canopy water loss was strongly related to tree mortality in the Sierra Nevada. Tubbesing et al. (2018) quantified and mapped standing dead biomass resulting from the recent tree mortality event with aerial detection surveys. They estimated that there is 80.7 million metric tons of standing dead biomass, with the majority in the southern Sierra (e.g., approximately 83% in Tulare, Fresno, Madera, Tuolumne, Mariposa, Kern, Calaveras, and El Dorado counties).

Young et al. (2017) found that the hottest, driest areas in California forests (i.e., higher mean annual climatic water deficit) and areas with denser stands experienced the highest tree mortality. An aridity-density interaction was observed, with a greater competition effect in drier areas.³ These results support the contention that altering the historic fire regime through fire suppression increased stand density and likely

³ Specifically, Young et al. (2017) reported that their model and data suggest that stands with low live basal area (e.g. 44 ft² ac⁻¹) can exist at relatively high mean annual climatic water deficit (CWD) (e.g. > 30 in) without experiencing substantial drought-related tree mortality. However, in stands with intermediate to high basal area (e.g. > 131 ft² ac⁻¹), substantial mortality occurred even in locations with moderate mean annual CWD (e.g. > 24 in).

increased drought vulnerability. In a study of treatments in the Kings River Experimental Watershed, Lydersen et al. (2019) found treatments that had negligible effect on basal area, tree density and canopy cover did not significantly influence tree mortality. These findings suggest that while treatments can be protective, some forest management treatments have not been conducted at a large enough scale or intensity to reduce drought vulnerability. Management implications include reducing drought vulnerability by focusing forest treatments (e.g., forest thinning) on the densest areas and utilizing prescribed fire on the driest sites to reduce future tree mortality.

Aerial detection survey results from 2017 showed greater true fir mortality in the higher elevations of the Sierra Nevada, and a greatly reduced rate of pine mortality in the lower elevations (USDA 2017a). The 2017 water year was one of the wettest in California's recorded history and may be partly responsible for these changes. Long-term precipitation data for California illustrate how the drought period for water years 2012-2016 compares to data from other water years (Figure 2). The 2018 water year was below average. Total precipitation in the northern and central Sierra Nevada was approximately 75% of normal, and it was about 60% of normal in the southern Sierra Nevada (CDWR 2018).

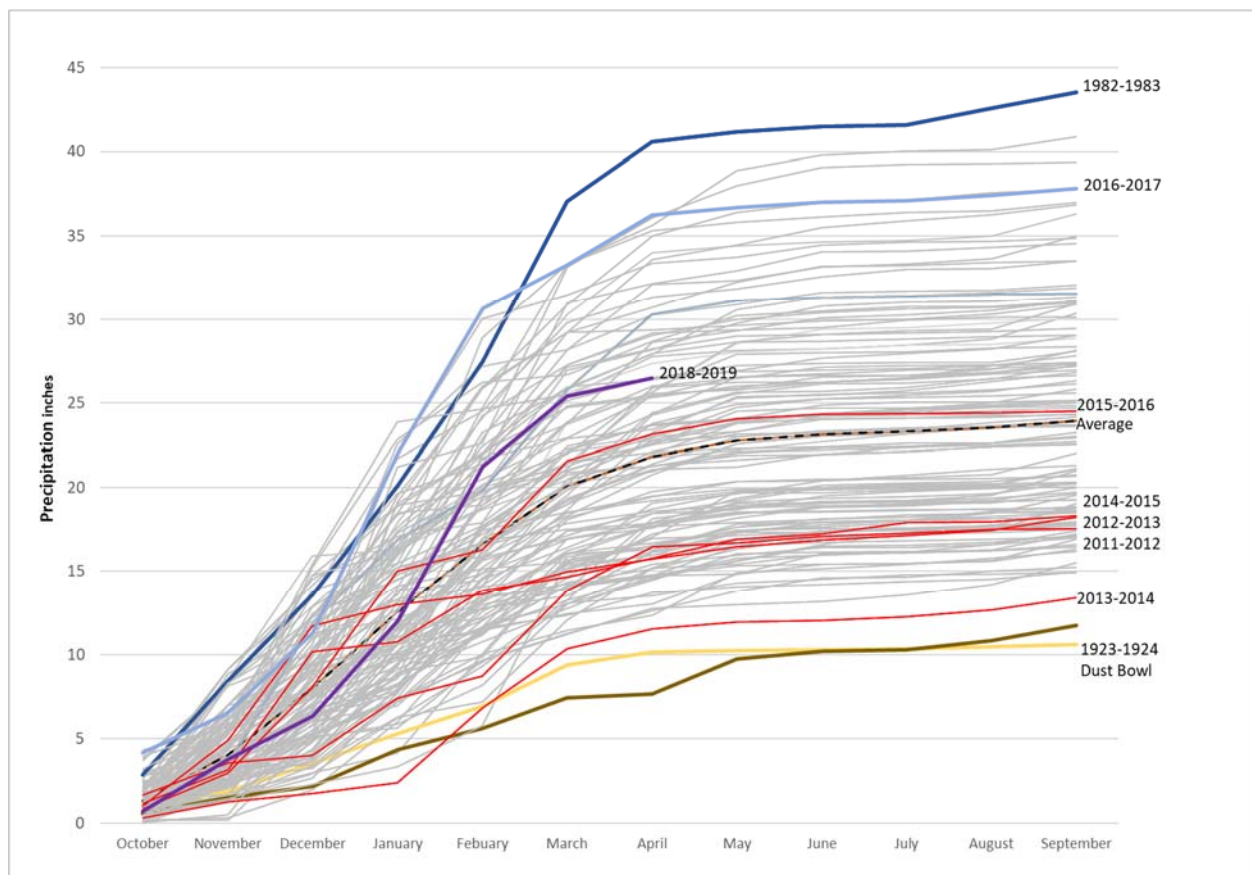


Figure 2. Cumulative statewide precipitation, 1895-present. Red lines represent drought water years 2012-2016; the dashed line is the historic average.

At the stand scale, Restaino et al. (2018) collected plot data from the Eldorado National Forest, Stanislaus National Forest, Yosemite National Park, and Sierra National Forest and found higher tree densities resulted in greater tree mortality. A clear gradient in treatment effectiveness was observed from north to south, with treatment effectiveness diminishing in the southern sites due to greater drought stress. When comparing paired treated and untreated sites in the central and southern Sierra Nevada, Restaino et al. (2019) found the probability of individual tree mortality of ponderosa pine was significantly lower in treated stands, with an important determinant of mortality being the abundance of nearby host trees (medium- and large-size) for insect mortality agents. For other conifer species, they found mortality to be positively associated with basal area. Plot data were also collected during 2015-2017 throughout the Sierra National Forest, an area in the southern Sierra Nevada severely impacted by the current bark beetle epidemic. Rojas and Pile (2017) reported that populations of California black oak and California red fir were relatively stable in 2015-2016, while white fir and incense cedar had undergone some reduction, and sugar and ponderosa pine experienced large reductions (i.e., 50-75% of the trees died) (Figure 3). Pile et al. (2019) found greater stocking increased pine mortality at these study sites, especially for ponderosa pine, and lower overstory basal area increased survival for white fir.

Drought mortality plots across a north-south gradient in the Sierra Nevada, from the Plumas National Forest in the north to Mountain Home Demonstration State Forest in the south, show a clear north-south mortality gradient, with considerably greater

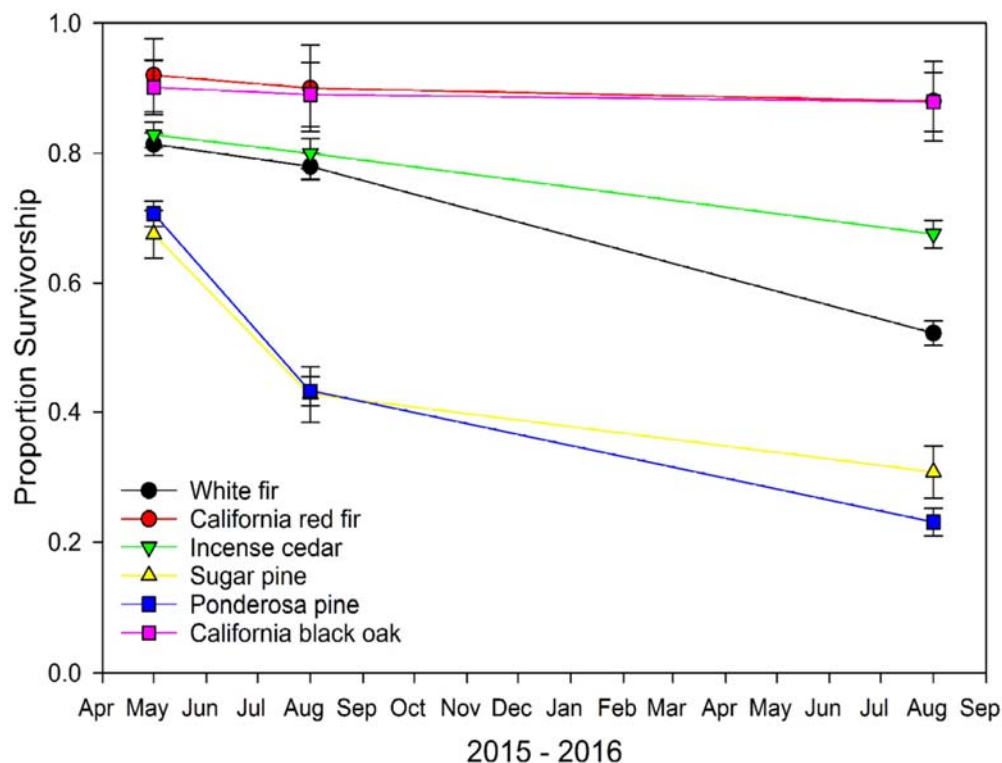


Figure 3. Plot data from the Sierra National Forest (Rojas and Pile 2017).

tree mortality in the southern plots (Figure 4; Axelson et al. 2019). In Yosemite and Sequoia-Kings Canyon National Park sites, a size class effect was evident. Mortality of incense cedar and black oak occurred in all size classes due to drought, whereas mortality for white fir, sugar pine, and ponderosa pine was concentrated in larger size classes, due to bark beetles' preferences for larger trees (Axelson et al. 2018). Mortality resulted from both beetle impacts (western pine beetle, mountain pine beetle, Jeffrey pine beetle, and fir engraver) and non-beetle causes, which could reflect disturbance interactions between forest disease and drought or drought alone.

Results from 2017 indicated that fir engraver beetles were found to be a key emerging threat, and they have not been confined to just the higher elevations. In 2018, mortality rates decreased to near zero in the northern Sierra (Plumas National Forest) and between 2-3% for all other sites, where mortality was higher in fir and cedar species than pines. Of the dead trees recorded, white fir experienced the highest fall rate with 3% per year and ponderosa pine had the lowest rate at just over 1% per year (Battles 2019). Regeneration measurements across the site network show that there were

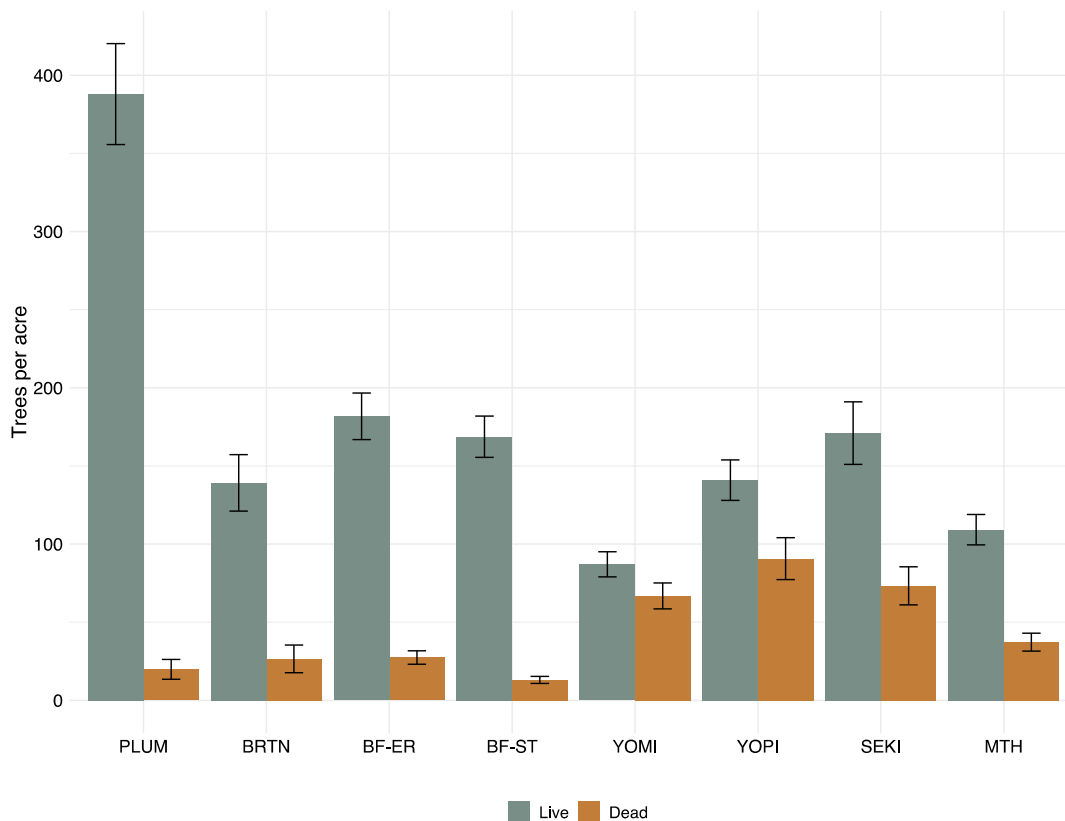


Figure 4. Recent (pre-2017 to 2018) tree mortality across a north-south gradient in the Sierra Nevada (Axelson et al. 2019). Site abbreviations: Plum (Plumas National Forest); BRTN (Burton Creek State Park); BF-ER (Blodgett Research Forest Ecological Reserve); BF-ST (Blodgett Research Forest Single Tree); YOMI (Yosemite National Park – mixed conifer); YOPI (Yosemite National Park – pine); SEKI (Sequoia-Kings Canyon National Park); MTH (Mountain Home State Demonstration Forest).

limited ponderosa and sugar pine seedlings and much greater amounts of white fir and incense cedar (Figure 5). For example, in Sequoia-Kings Canyon plots seedlings and saplings are dominated by incense cedar, California black oak, and white fir (Axelson et al. 2019). Plots will continue to be monitored for tree mortality, tree fall rates, surface fuels accumulation, and regeneration.

Fettig et al. (2019a) reported results from 180 37-foot fixed radius plots installed on the Eldorado, Stanislaus, Sierra, and Sequoia national forests. Approximately 49% of trees died between 2014 and 2017 (Figure 6). Tree mortality ranged from $46 \pm 3.3\%$ on the Eldorado National Forest to $59 \pm 3.7\%$ on the Sierra National Forest. Significantly higher levels of tree mortality occurred at low elevations ($60 \pm 3.0\%$) compared to high elevations ($46 \pm 2.9\%$). Ponderosa pine exhibited the highest levels of tree mortality (90%), with 39% of plots losing all ponderosa pine. Mortality of ponderosa pine was highest at the lowest elevations, concentrated in larger diameter trees, and attributed primarily to colonization by western pine beetle. About 89% of ponderosa pine in the three largest diameter classes were killed, representing loss of an important structural component of these forests with implications for special status wildlife species. Sugar pine exhibited the second highest levels of tree mortality (48%). Mortality of sugar pine was concentrated in the mid-diameter classes and attributed primarily to colonization by

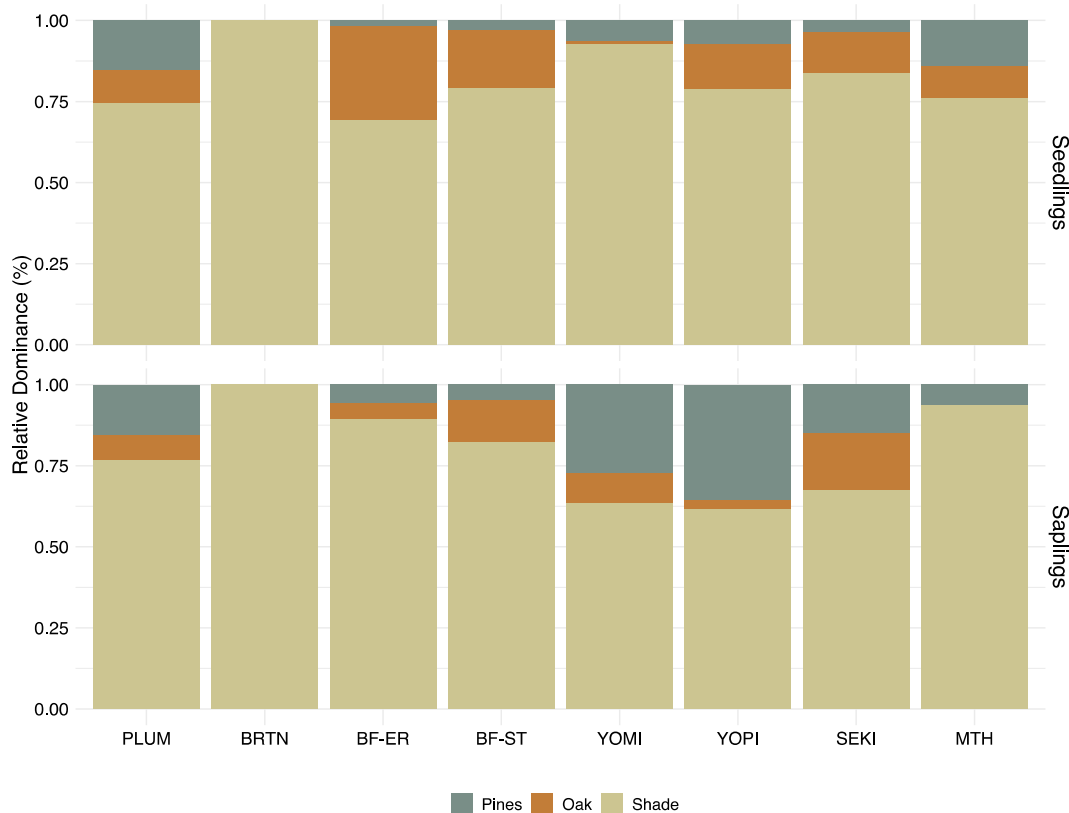


Figure 5. Relative dominance of seedlings (top) and saplings (bottom) across a north – south gradient in the Sierra Nevada (Axelson et al. 2019). Most sites are dominated by shade tolerant species which include white and red fir and incense cedar. See Figure 4 for site abbreviations.

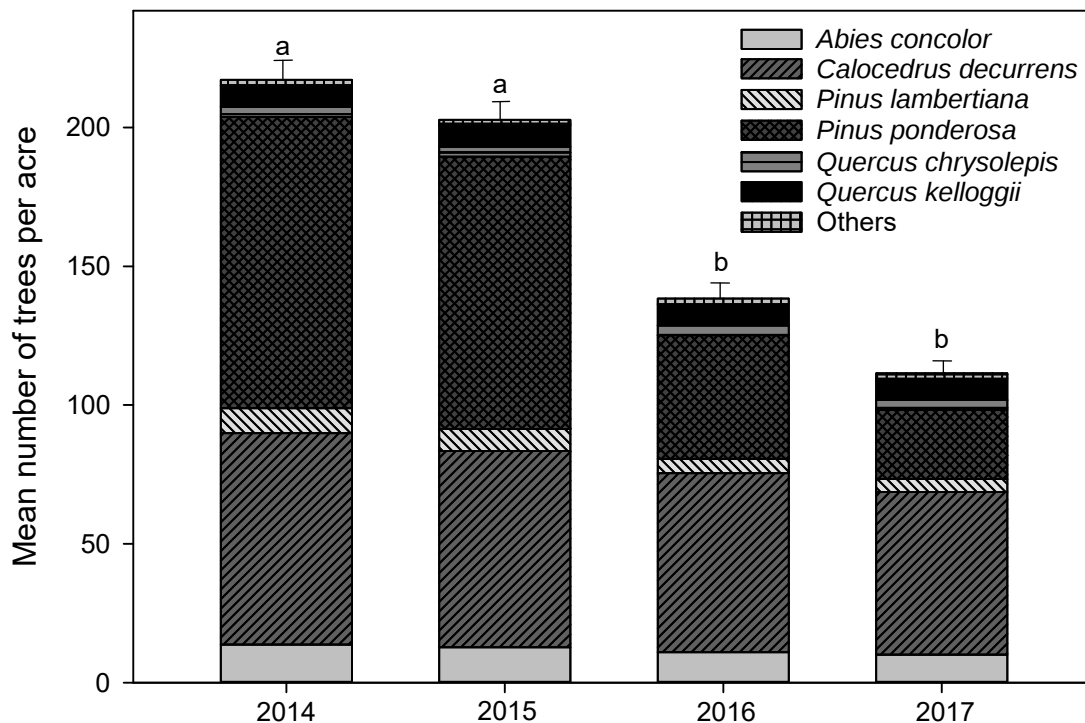


Figure 6. Mean number of trees (+ standard error of the mean or SEM) for plots installed on the Eldorado, Stanislaus, Sierra and Sequoia national forests, 2014–2017. Means (+ SEM) followed by the same letter are not significantly different (from Fettig et al. 2019a).

mountain pine beetle. White fir and incense cedar exhibited 26% and 23% mortality, respectively, and black oak mortality was nearly non-existent. Tree mortality was positively correlated with tree density and slope. Tree regeneration (seedlings and saplings) was dominated by incense cedar and oak species, representing a potential shift in composition from forests that were dominated by ponderosa pine. Snags have already fallen and become part of the surface fuel profile; plots will be monitored on an annual basis for causes and magnitude of tree mortality and snag retention.

Landownership Data in the Sierra Nevada

Different landowners in the Sierra Nevada have different objectives for their forestland. In the heavily impacted areas of the 10 high priority counties,⁴ GIS analysis using 2016 tree mortality data shows the following for landownership categories: industrial lands–

⁴ High priority counties identified by the Tree Mortality Task Force (TMTF) as having severe tree mortality are Placer, El Dorado, Amador, Calaveras, Tuolumne, Mariposa, Madera, Fresno, Tulare, and Kern; see: http://www.fire.ca.gov/treetaskforce/downloads/TMTFMaterials/Tier1_Tier2_HighHazardZones_Statewide_2018_85x11.pdf

6% of forested area, federal lands–76% of forested area, and private nonindustrial–18% of forested area (Table 1).⁵ In the long-term after drought-related tree mortality subsides, species composition in this region is expected to vary considerably depending on the type and amount of salvage harvesting, reforestation, and forest management practices that occur on these different types of ownerships.

The majority of tree mortality observed in the 2016 aerial detection surveys (ADS) occurred on federal land, with 60% occurring on working public lands and 16% occurring on public lands with special management restrictions (e.g., wilderness) (Figure 7, public unavailable).⁶ The remainder of tree mortality occurred on private land, with 17% on nonindustrial and 7% on industrial. As a percent of the total amount in each ownership category, public working lands were most affected with 39% mortality, followed by private industrial with nearly 33% mortality, private nonindustrial with 29% mortality, and public unavailable having the lowest mortality at 17% (Table 1, Figure 7).

Changing land ownership patterns in the Sierra Nevada will also impact future management actions in this region. The development of communities and infrastructure across the lower Sierra foothills may be as important as ecological processes in affecting long-term changes in forest composition in this elevation band (3,000 to 5,000 feet).⁷ Conversion of forestland to other uses (e.g., residential development, recreational areas, vineyards, and cannabis cultivation) presents a large challenge to maintaining healthy forests where they have historically been present in the Sierra Nevada.

Table 1. Forested area and observed area of tree mortality in 2016 by management category in the 10 designated high priority counties. Sources: USFS Aerial Detection Survey (ADS) 2016, CAL FIRE-FRAP Management Landscapes 2015.

Ownership Category	Forest Area (acres)	Forest Area (percent)	2016 Mortality (acres)	2016 Mortality (percent)
Private - Nonindustrial	1,105,728	18.2%	322,000	29.1%
Private - Industrial	375,499	6.2%	123,000	32.7%
Public - Unavailable	1,741,352	28.7%	304,000	17.5%
Public - Working	2,849,888	46.9%	1,117,000	39.2%
All Categories	6,072,467	100.0%	1,866,000	30.7%

⁵ Ownership classes are only on forested land, as defined by the CAL FIRE-FRAP vegetation GIS layer, updated in 2015. Mortality polygons are from the USFS Aerial Detection Survey (ADS) and they sometimes overlap between years, so only 2016 data are presented. Estimated mortality from 2010-2015 was 40 million trees; for 2016 alone it was 62 million trees. Through 2018, estimated mortality was 147 million trees.

⁶ ADS is conducted preferentially on USFS lands, without complete coverage of the entire state.

⁷ California's population has increased from 15,000 to 150,000 pre-European settlement in 1840 to almost 40 million today. Massive land use changes have occurred over the past 180 years.

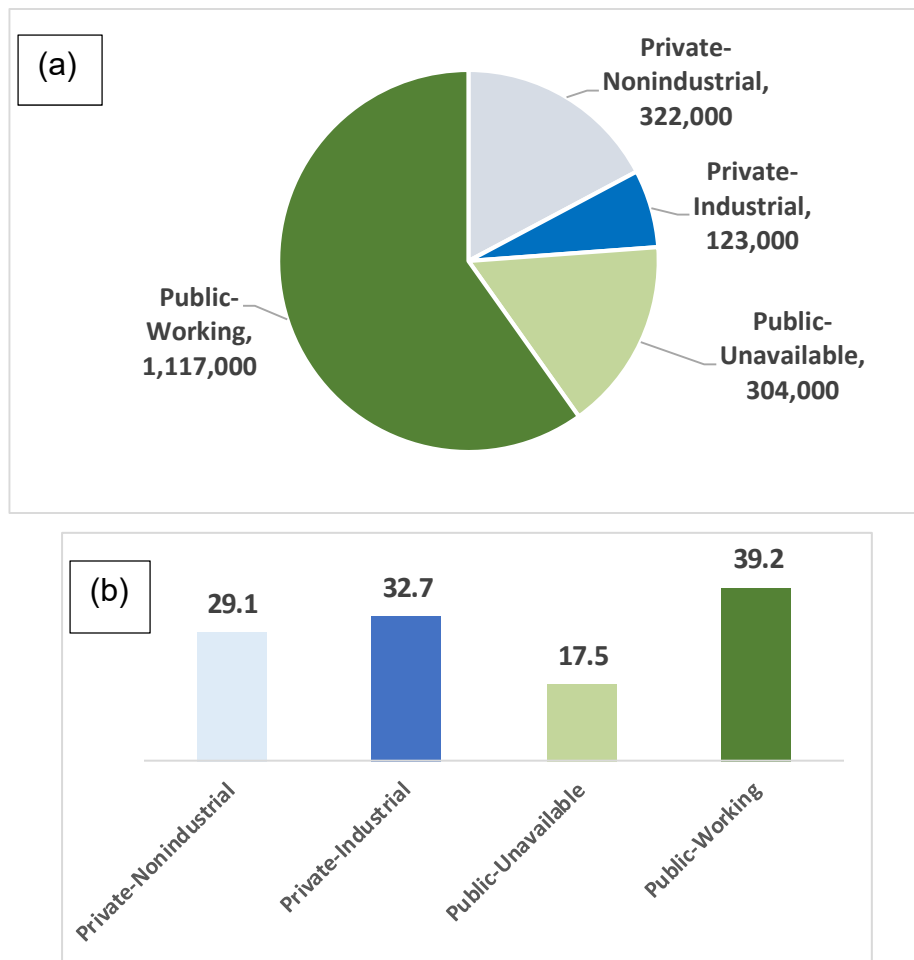


Figure 7. Area of new tree mortality detected in 2016 given as (a) total acres by management category in the 10 high priority counties, and (b) the percent of the management category (forest area only) affected in 2016 in the high priority counties.

Potential Changes in Fire Behavior due to the Bark Beetle Epidemic

There is debate over the extent to which insect epidemics may alter the likelihood of fire occurrence, fire intensity, and fire severity in post-epidemic residual vegetation, with some studies from other regions suggesting no consistent effect on these wildfire characteristics (e.g., Meigs et al. 2016). However, post-epidemic fire behavior in a Mediterranean climate with frequent fire-adapted forests dominated by long-needle pines have had relatively little study. Major questions remain about future fire risk in forests with widespread and severe tree mortality, and changes in species dominance from fire resilient pines to less adapted species such as white fir and incense cedar.

On a stand-level, or the level of an individual fire, the accumulation of dead and downed fuel and standing dead trees is expected to increase fire intensity, and pose significant hazards for fire control efforts and public safety. For example, the 2012 Chips Fire (Plumas County) had high tree mortality from previous wildfires combined with a brushy understory and steep terrain. This resulted in a fire with a very high resistance to control, even under low wind conditions (Fites et al. 2012). These conditions have also been anecdotally noted for more recent (2014-17) fires burning in areas of high tree mortality,⁸ but studies aimed at understanding mortality effects on residual stand fire severity, resistance to control, or its contribution to overall area burned across the region have only recently started. The scale of the tree mortality event in California is so large that a greater potential for “mass fires” exists, driven by the amount and continuity of dry combustible large woody material which could produce large, severe fires (Stephens et al. 2018). For example, Battles (2018) modeled a 330% increase in dead tree biomass from 2014-2017 mortality for plots installed in Sequoia-Kings Canyon National Parks. The 1000+ hour fuel loads were modeled to double by 2030, with 75% of the plots having fuel loads greater than 100 tons/acre.⁹ The temporal dynamics of drought and insect-related tree mortality create additional complexity, as standing dead trees fall down over years or decades.¹⁰

Lessons Learned from Bark Beetle Epidemics

Large scale bark beetle epidemics have been studied in several areas in western North America during the past two decades. For example, in British Columbia, Canada over 44 million acres were impacted by a mountain pine beetle epidemic from the late 1990s to approximately 2014, which are described in several published papers. In central British Columbia, mortality of 70-80% caused the overstory to shift to an uneven-aged lodgepole pine forest, while the understory returned to lodgepole and increased aspen (Axelson et al. 2010). In southern British Columbia, lodgepole pine forest plots revealed a shift in the size structure of stands and a shift in regenerating species. Lower intensities of tree mortality did not result in significant increases in light reaching the forest floor, favoring regeneration of shade tolerant tree species (e.g., Douglas-fir and spruce) (Axelson et al. 2009).

⁸ During the 2014 fire season, the Courtney Fire in the Madera-Mariposa-Merced Unit (MMU) burned in an area with significant tree mortality, where the trees had dry needles that led to long range spotting and hampered control efforts. The 2017 fire season produced several fires (e.g., Mission, Spring, and Peak fires in MMU) in areas with standing dead trees that burned hot and quickly, impeding control efforts due to spotting and rapid tree fall without warning (CAL FIRE Battalion Chief Frank Bigelow, Fresno, CA, personal communication).

⁹ 1000-hour fuels are 3 to 8 inches in diameter.

¹⁰ Keen (1955) reported that the half-life of ponderosa pine snags was approximately 8 years in southern Oregon and northeastern California (i.e., cooler/drier climates than are found in the central and southern Sierras). Ponderosa pine snag longevity in the 2012-2017 Sierra Nevada tree mortality event is expected to be shorter than that reported by Keen (1955). Snag failures have already been observed on monitoring plots installed within affected areas on the Eldorado, Stanislaus, Sierra and Sequoia national forests (C. Fettig, USFS PSW, personal communication). Additional information on snag fall rates for California conifers is provided by Cluck and Smith (2007).

In southern Alberta, sites with 10-93% mortality of the overstory shifted from lodgepole pine to a mixed species canopy, and the understory became dominated by shade tolerant tree species (e.g., subalpine fir, balsam poplar) with no pine regeneration (Axelson et al. 2018). These shifts have resulted in stands with greater heterogeneity, greater abundances of non-pine species, and reduced probability of beetle epidemics in the future due to succession towards higher proportions of non-host tree species. In the northern Rocky Mountains (Idaho and Montana), seedling density did not increase significantly following bark beetle epidemics until the “gray” tree mortality phase, when the canopy became sufficiently open (Stevens-Rumann et al. 2015).

British Columbia, Montana, and Idaho, which have all experienced bark beetle epidemics, are energy-limited systems. This means that the types of trees and more importantly the shrub/grass species that take advantage of reduced crown cover are limited. This is not the case in California, where the Mediterranean climate enables numerous shrub, grass, and invasive plant species to establish, which could alter forest dynamics.

The closest large-scale bark beetle epidemic to the current Sierra Nevada event occurred in southern California in the early 2000s (Fettig 2019). Walker et al. (2006) reported approximately 12.7% of conifers died between 2001 and 2004. Fir experienced the largest amount of mortality (39%), followed by pine (23%), pinyon-juniper (22%), hardwoods (13%), and subalpine mixed conifer (3%). Mortality was widespread and concentrated in several tree species, most notably ponderosa and Coulter pine, where it was primarily attributed to western pine beetle. Mortality was greater than 80% in some areas (e.g., portions of San Diego County). Ponderosa and Coulter pines greater than 17 inches in diameter experienced 73.5% and 78% mortality, respectively. Despite continuing drought and availability of suitable host trees, western pine beetle populations rapidly declined in 2004 (Hayes et al. 2009). While little has been published on this epidemic, some type conversions were reported for the most heavily impacted areas (Walker et al. 2006). For example, in San Bernardino County, more than 7,000 acres were converted from mixed-conifer and hardwood forests to nearly pure hardwood. Approximately 1,500 acres previously classified as conifer forest is now shrubland (Walker et al. 2006). Fettig (2019) concluded the southern California epidemic provides insight into what socioecological (i.e., social and biophysical) impacts are likely to be of most concern in areas impacted by the current epidemic, useful in bolstering our capacity to prepare for and respond to such large-scale forest disturbances.

Projected Impacts from Climate Change on Sierra Nevada Forests

Climate change is expected to impact Sierra Nevada forests in a variety of ways, likely causing major effects. By itself, a changing climate will affect the capacity for both individual species and broad forest types to persist on the landscape. In a climate exposure analysis of six California Wildlife Habitat Relationship (WHR) vegetation types, Thorne et al. (2017a) estimated that Sierran Mixed Conifer (SMC) forests will experience considerably more climate-induced stress by the late 21st century, especially

under current levels of greenhouse gas emissions (RCP 8.5) and hotter/drier conditions (MIROC climate model projections).¹¹ They indicated that 226,000 acres of this forest type are currently under climate stress, defined as experiencing climatic conditions in the top 5% of the range of variation for the type. Under current greenhouse gas emission levels with a hotter and drier future, over 2.5 million acres of this forest type will be similarly climate-stressed by the late the 21st century, or will be exposed to climate conditions that currently have no analog in California. An analysis of a lower emissions scenario (RCP 4.5) with a warmer and wetter future (CNRM climate model) still projected a significant increase in climate stress for SMC forests, with 465,000 acres exposed to climate stress.

Similarly, a broader analysis of southwestern forests (California, Nevada, Utah, Arizona, and New Mexico) found that by the late 21st century, 27-77% of forests in this region will be climatically exposed under wetter or drier conditions at current emissions levels (RCP 8.5), while reduced emission levels are modeled to produce 10-50% exposure. Forests in central Arizona and the western slope of the Sierra Nevada were found to be particularly vulnerable (Thorne et al. 2017b).

Analyses of climatically suitable ranges for 31 individual conifer and hardwood tree species in California (Thorne 2017a) found that by the end of the century, as many as 15 species will lose over 75% of their current climatically suitable range under the current emissions track (RCP 8.5). Among the most vulnerable are whitebark pine, California red fir, Coulter pine, and giant sequoia. Some tree species gain additional climatic suitability in their analyses, but whether they can become established in these areas is unknown.

Current science suggests that climate change will produce higher temperatures and more severe and prolonged droughts in California. The co-occurrence of unusually warm and unusually dry years has led to more frequent hot droughts in recent decades (Diffenbaugh et al. 2015). While uncertainty exists in predictions of future precipitation, regional warming will mean that dry years will be more likely to coincide with hot years, leading to more frequent and severe droughts in the future. Increasing tree moisture stress resulting from both droughts and altered stand conditions will likely lead to extensive bark beetle epidemics (Kolb et al. 2016), as we have experienced in the current epidemic. In other words, the current bark beetle epidemic is not expected to be a one-time event as long as susceptible tree (host) size classes exist. Therefore, in an effort to reduce the impact of the next drought, forest owners and managers should consider reducing tree densities through mechanical thinning and fire (both prescribed and managed wildfires) (Fettig et al. 2019b). Given the spatial scale of the Sierra Nevada, priority should be given to watersheds that provide critical water supply or contain critical water infrastructure, forested areas with residential communities, or areas with important wildlife habitat (TMTF 2017).

¹¹ Representative Concentration Pathways (RCPs) are four greenhouse gas concentration trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC) for its fifth Assessment Report (AR5) in 2014. MIROC (Model for Interdisciplinary Research on Climate) is one of several general circulation models (GCMs) available for studying climate change impacts.

Increases in wildfire activity in the Sierra Nevada in recent decades (Miller and Safford 2012) have also been tied in part to climate change through earlier spring snowmelt and decreased fuel moisture (Westerling 2016, Abatzoglou and Williams 2016, Crockett and Westerling 2018). The interactions of climate change, altered forest stand conditions, increasing wildfire activity, bark beetles, and tree mortality are expected to produce major changes in species composition, including exotics (Liang et al. 2016, Littell et al. 2016, Figure 8).

For example, Shive (2017) studied two sites in Yosemite National Park that had burned twice in less than 30 years. She installed plots in areas that experienced high burn severity twice and areas that burned at high severity only once. Species richness, plant cover, shrub biomass, and conifer regeneration density were recorded for each area. Repeated high severity fire was found to shift dominance to sprouting species and nonnative annual grasses, resulting in more distinct plant communities, lower overall species richness, and a higher proportion of south-temperate species.¹² Areas twice-burned at high severity also had significantly fewer conifer seedlings, suggesting that transition from forests to shrub and grasslands was resulting from intense wildfires that killed conifer seed sources.

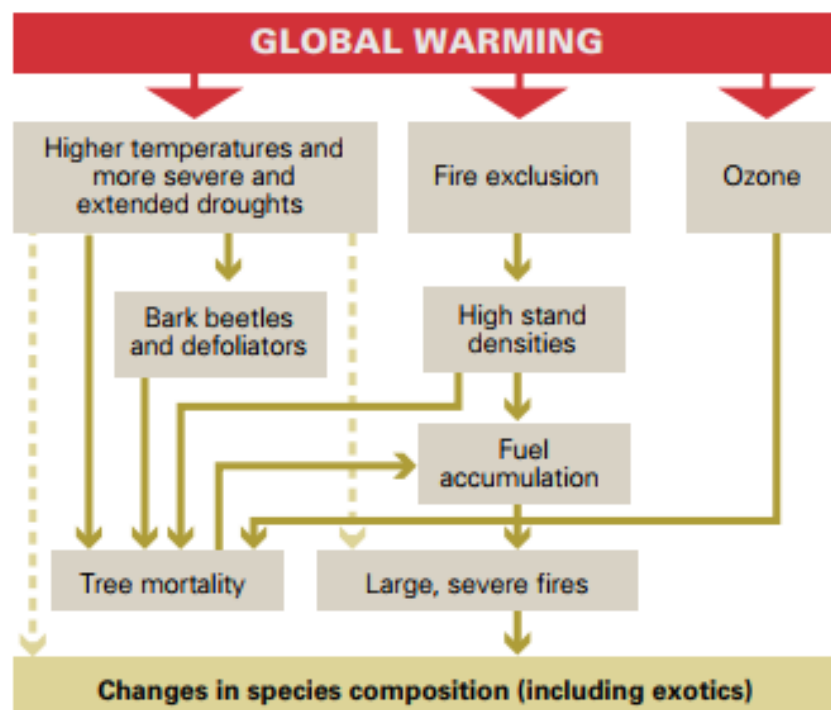


Figure 8. Global warming impacts on tree mortality and species composition (from Littell et al. 2016).

¹² Plant species were defined as north- and south-temperate in biogeographic affinity (i.e., the general climatic tolerances of taxa based on climatic conditions of the region and time periods under which they evolved and diversified (Wiens and Donoghue 2004)).

Stevens-Rumann et al. (2017) studied post-wildfire conifer regeneration in the Rocky Mountains and reported significant decreases in tree regeneration, when compared with the 20th century. There were greater annual moisture deficits from 2000-2015 compared to 1985-1999, suggesting poor post-fire growing conditions, which corresponded to lower seedling densities and greater regeneration failure. They concluded that dry forests that already occur at the edge of their climatic tolerance are most prone to conversion to non-forests after wildfires.

Young (2017) reported on how weather patterns in the years following wildfire affect forest regeneration in mixed-conifer forests in northern California. Data were collected from 535 plots located in 14 fires that burned in 7 different years. Weather parameters determined whether the first 3 years after the fire were categorized as wet or dry. Shade tolerant conifer (e.g., white fir) regeneration was more impacted by dry conditions than that of more drought tolerant pine species, but all conifer regeneration decreased with drought conditions. Shrub species percent cover increased under drought conditions, while hardwood species that sprout were relatively insensitive to drought. Young concluded that post-fire drought will likely reduce regeneration of conifers, especially shade-tolerant species, supporting model-based projections that shrub and hardwood species will increase in dominance as drought becomes more common. Similarly, Petrie et al. (2017) reported that climate change may start to restrict the persistence and expansion of dryland forests (i.e., ponderosa pine forests in the western U.S.) by limiting ponderosa pine seedling survival in the late 21st century.

Projected Long-Term Changes in Sierra Nevada Forest Composition

There are many unknowns regarding Sierra Nevada forest recovery from the current beetle epidemic, including (1) Will there be conversions to other forest types or shrubs? (2) Will ponderosa pine be lost at lower elevations? (3) Will ponderosa and sugar pine across heavily affected areas sufficiently regenerate? and (4) Will fuel accumulations change fire behavior and/or impede forest regeneration? Unfortunately, past studies in other parts of the western hemisphere do not help us answer these questions. California's Mediterranean climate and abundant shrubs will significantly affect post-mortality recovery, making the Sierra Nevada's outlook different than areas with colder climates.

The limited data available from the recent southern California bark beetle mortality event indicate that type conversions in some areas are likely, particularly where active forest management practices are not implemented. The heavy loss of ponderosa pine and sugar pine creates conditions that limit the potential for natural pine regeneration (Rojas and Pile 2017). Unlike after wildfire, the bare mineral soil required for pine regeneration is largely absent following bark beetle epidemics. Low pine survival creates opportunities for the rapid increase of shrubs and noxious weeds.

The outlook for long-term Sierra Nevada forest composition depends on several factors including elevation, aspect, ownership category, soil type, precipitation trends (magnitude and phase), post-bark beetle epidemic wildfire history, and latitudinal

position in the Sierra Nevada (e.g., northern, central, or southern). It is difficult to predict what will happen at specific sites along the western slope of the southern and central Sierra Nevada after the current bark beetle epidemic. We can, however, attempt to model overall patterns and identify general areas at particular risk for type conversion. It is expected that the lower elevation areas most likely to experience type conversions from mixed-conifer forest to shrub and oak/grass/woodland types are those that:

- Have experienced severe tree mortality.
- Have experienced intense wildfire following severe tree mortality.
- Have south facing aspects.
- Have shallow, skeletal soils with low water holding capacity.¹³
- Are located in the southern Sierra Nevada at lower elevations.
- Are not industrial timberlands.

We performed a GIS overlay analysis for a small part of the Sierra Nevada as a proof of concept for a type conversion risk assessment. We chose the Sierra National Forest, as it has experienced severe tree mortality (Rojas and Pile 2017, Fettig et al. 2019a) and has a significant amount of private nonindustrial forestland. The following GIS layers were used, representing the variables listed above, and scored for risk of type conversion:

- **Tree mortality** – Areas with greater than 40 dead trees per acre from 2012-2017, as reported by ADS.
- **Southern aspect** – South, southeast, and southwest aspects.
- **Very high fire threat** – Areas modeled as having a very high fire threat (CAL FIRE-FRAP assessment).
- **Topographic position** – Topographic positions favoring shallow regolith and low water storage (upper slopes, ridges, and convex slopes). Topographic position was used to model the interaction of soil, geology, and topography. Soil mapping in mountainous areas of California has not been done at a scale and consistency to be useful.
- **Climatic exposure** – A synthesis of a spatial climate model to indicate areas at risk for species shift due to climate change (Thorne et al. 2017a).

Industrial forest landowners will likely rapidly restock conifer seedlings and use forest management practices to enhance survival. Since these intensively managed forests likely have limited risk of type conversion, we limited the analysis to nonindustrial

¹³ Digital data for soil depth to hard bedrock is desirable for this analysis but is not currently available. Soil depth to soft bedrock is not as useful, since trees use water in deep weathered regolith (Ferrell et al. 2017).

forestlands. Additionally, the analysis focused on the elevation band from approximately 2,000 feet to approximately 7,000 feet, as drought-incited tree mortality has primarily affected conifer species that are found at those elevations.

The analysis used 30-meter grid representations of the five variables for an area encompassing 1,094,877 acres or approximately 77% of the Sierra National Forest (Figure 9). Each variable's grid was calculated as a binary value of 1 or 0, where 1 represents a risk of type conversion and 0 represents no threat. The grids were added together and the resulting grid represents a risk surface with potential risk values ranging from 0 (least threat) to 4 (greatest threat).¹⁴ Risk values from 1 to 4 were grouped into four categories to indicate low, medium, high, and very high risk of forest type conversion.

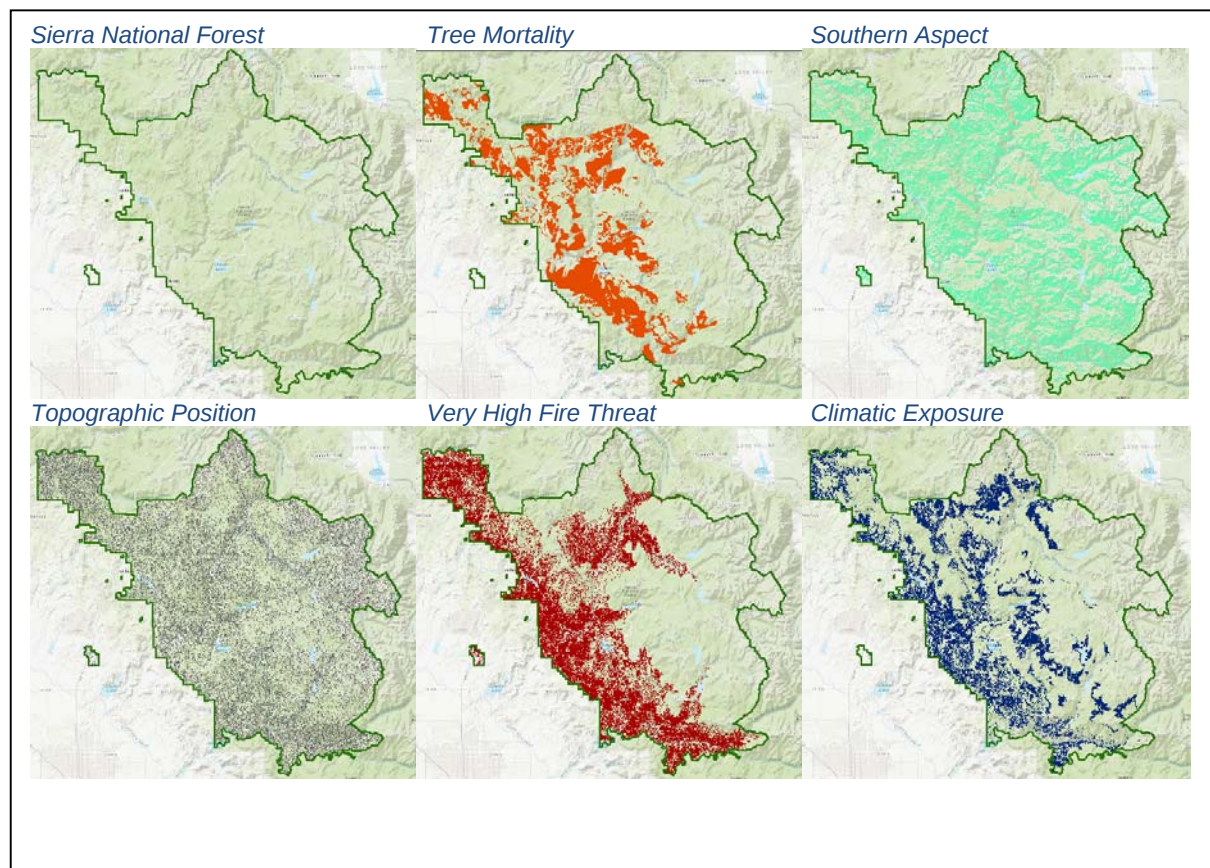


Figure 9. Variables for risk of forest type conversion in the Sierra National Forest (colored areas are higher risk).

¹⁴ Most Likely for Type Conversion = (Mortality) + (Aspect) + (Fire Threat) + (Topographic Position) + (Climatic Exposure).

The results indicate that the majority of areas at greater risk for forest type conversion lie within the lower part of the ponderosa pine elevation band that ranges from 2,000 feet to about 7,000 feet (Figure 10). As very high fire threat and climatic exposure were also concentrated in this elevational range, it follows that the areas at greatest risk for type conversion would also be in that area. There is a small amount of the highest risk category (4%), which may be due to the fact that topographic position was mapped at a much finer resolution than the other datasets. Approximately 12% of the total Sierra National Forest was found to be at high risk, and 60% at low to moderate risk for type conversion. About 23% of the Sierra National Forest was rated as having no risk using the factors listed above (Table 2).

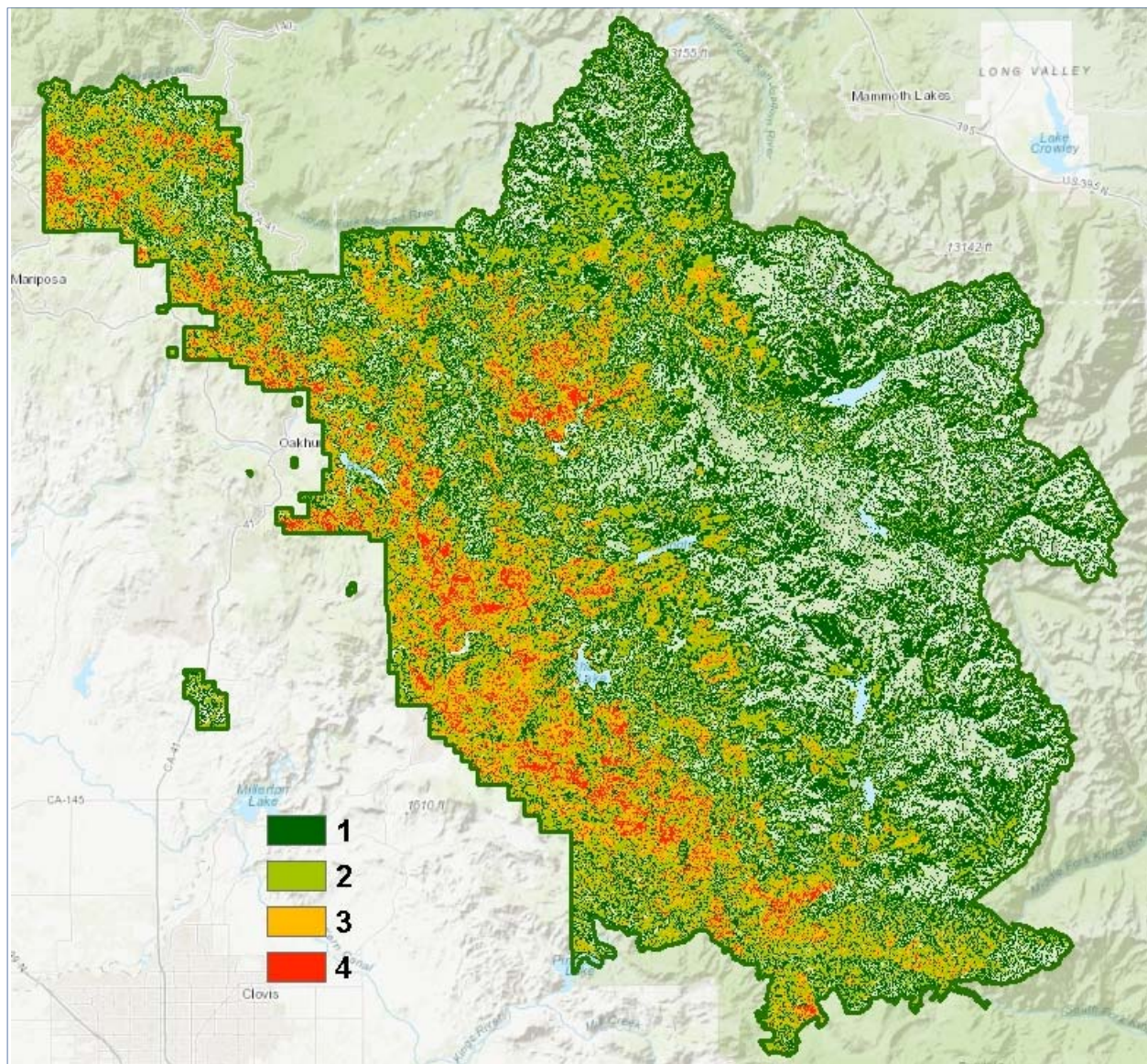


Figure 10. Risk of forest type conversion in the Sierra National Forest. Risk value 1 = low, 2 = medium, 3 = high, and 4 = very high.

Table 2: Risk of forest type conversion in the Sierra National Forest (SNF).

Risk Level	Acres	Percent of Total SNF
0	323,860	23
1	509,423	36
2	355,738	25
3	172,886	12
4	56,830	4

There are several variables that we were not able to incorporate that would improve this model and lead to better understanding of areas at greatest risk for type conversion. These include:

- **Stand density:** Stand density has been shown to positively correlate with tree mortality (Young et al. 2017, Bradford 2018). A reliable and consistent dataset that covers the Sierra Nevada depicting stand density was not available. New acquisitions of remotely sensed data such as LiDAR and multispectral imagery will enable reliable and consistent stand density mapping.
- **Conifer species:** Drought and bark beetle mortality has been shown to affect species differently (Thorne et al. 2017a, Fettig et al. 2019a). This analysis could be improved by targeting the species of concern (e.g., ponderosa pine) by size class.
- **Local environment:** Local environmental conditions have been shown to be a significant factor in tree mortality during drought (Young et al. 2017, Paz-Kagan et al. 2017). Developing a dataset that covers the Sierra Nevada and that provides a better representation of regolith thickness, distance to streams, soil depth, and climatic water deficit would substantially improve the analysis.
- **Regeneration:** Little is known about the effect this tree mortality event will have on regeneration (Young et al. 2017). Many studies are evaluating regeneration in sites with varying levels of overstory mortality. These studies will inform future analyses about where regeneration is occurring and what species are regenerating, improving our understanding of future conditions.

In addition to adding these variables, improved modeling techniques could also improve future analyses. Statistical modeling, such as the Random Forest algorithm (Paz-Kagan et al. 2017), would allow a best-fit model approach to use local environmental factors, along with biotic factors such as tree species, stand density, and regeneration. Such a model would also make it possible to screen for collinearity in data. For example, Paz-Kagan et al. (2017) found significant overlap between elevation and climate model data.

In general, this analysis is meant to provide a starting point for thinking about how to prioritize forest restoration after a massive tree mortality event. Removal of dead trees is costly, but successful reforestation is also expensive and should be rationally planned. Identifying areas where replanting will be challenging can inform the restoration strategy and direct resources to areas where they are most likely to result in successful survival of planted seedlings (North et al. 2019). Conversely, if the cost is determined to be prohibitive, some sites may be left to regenerate naturally and type conversion allowed to occur. Planning may be structured around watershed restoration. In that case, areas in watersheds with the least amount of high risk may be prioritized for reforestation.

The results of this modeling exercise for risk of type conversion are generally consistent with those presented by other studies. For example, Paz-Kagen et al. (2017) attempted to predict areas of tree mortality using local environmental factors. The area studied covered 32,200 acres, with an elevation range of approximately 3,200 feet to 11,000 feet, in Sequoia National Park. Advanced remote sensing technologies (i.e., LiDAR and HiFIS) were used to map tree mortality and tree species composition. They found that there was a higher probability of tree mortality at lower elevations, on southwest and west-facing slopes, in areas with shallow soils, on shallower slopes, and at greater distances from water. Mortality was found to be species specific, primarily affecting ponderosa and sugar pine at lower elevations. They concluded that selective mortality may cause long-term shifts in forest community composition (Paz-Kagen et al. 2017).

Additionally, the 2017 FRAP assessment reports that loss of current timberlands is expected to be most extensive in the lower elevations of the southern range of the Sierra Nevada (FRAP 2018). Based on climate change modeling completed by Thorne et al. (2017a), the assessment indicates that by 2069 California's Southern Forest District could lose between 0.4 million acres (15% of District timberland) under a warmer/wetter climate change modeling scenario, and 0.8 million acres (29%) under a hotter/drier scenario.

Reforestation in the Aftermath of Massive Tree Mortality

Reforestation efforts and early stand treatments (e.g., competing vegetation control, pre-commercial thinning) may be necessary to create favorable conditions for conifer regeneration in many stands following the current bark beetle epidemic. This is actively occurring on industrial timberlands in the Sierra Nevada, but their ownership only occupies about 6% of the highly impacted region affected. For the federal and private nonindustrial lands, a collaborative reforestation strategy is under development. Guidelines for all nonindustrial lands will likely stress reforestation on higher productivity sites, using a mixture of conifer species, and planting at lower densities and with special arrangements to produce greater resilience to drought and fire (e.g., cluster planting on mesic microsites) (North 2017, North et al. 2019). Funding and staffing limitations, however, reduce the amount of the landscape that can be treated by the U.S. Forest Service, therefore federal and state partnerships are important to increase the amount

of reforestation work that can be undertaken on federal lands in the near future (Butsic et al. 2017, TMTF 2017).

Small nonindustrial private landowners have mixed objectives and opinions about reforestation. The amount of reforestation that will occur is unknown, but it is likely to be a relatively small percentage of this ownership category. There are several concurrent efforts in progress aimed at educating landowners on the need to reforest, and providing assistance with acquisition of seedlings and cost share funds to help them implement reforestation projects. There is a general recognition among land managers that some lower elevation and low site quality lands may not be actively reforested, and will be left to transition to oak and foothill pine-dominated woodlands.

Better information on potential natural recovery scenarios is needed to help inform landowners on where active reforestation is feasible, where reforestation may be unwise, and where natural reforestation may develop an altered, but acceptable future stand density. Documentation of expected natural recovery, either by elevation zones or existing vegetation types, will be beneficial for California forest landowners.

In summary, changes to disturbance regimes, continuing land-use changes, and climate change with associated species shifts all pose significant challenges for maintaining healthy and resilient forests in the Sierra Nevada. Significant unknowns exist regarding the future species composition for vast portions of this region, but type conversions from mixed conifer to shrublands or oak/grass/woodland appear likely for some areas. Recommended best management practices focus on reducing tree densities, achieving successful reforestation, and using adaptive management in the face of currently unknown future changes in growing conditions (Fettig et al. 2019b). Monitoring studies currently underway will provide data to help address these unknowns in the future.

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