



Mixed Evergreen Forests

Climate Change Vulnerability Assessment for the Golden Gate Biosphere Region

This document represents an evaluation of climate change vulnerability for mixed evergreen forests in the Golden Gate Biosphere (GGB) region of California. The following information is based on stakeholder input provided during and following a winter 2022 vulnerability workshop as well as sources from the scientific literature.

Ecosystem Description

Mixed evergreen forests are widely distributed across California, from the northern Klamath Mountains into the coastal mountain ranges and south into the Transverse and Peninsular ranges (Stuart & Stephens 2006; Sawyer 2007). This forest type is comprised of a mix of hardwoods and conifers, with a multi-layered canopy where the lower layer is composed largely of hardwood species (Sawyer 2007). Characteristic species in the Golden Gate Biosphere (GGB) region include Douglas-fir (*Pseudotsuga menziesii*), tanoak (*Notholithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), California bay laurel (*Umbellularia californica*), canyon live oak (*Quercus chrysolepis*), interior live oak (*Q. wislizeni*), coast live oak (*Q. agrifolia*), California black oak (*Q. kelloggii*), Oregon white oak (*Q. garryana*), golden chinquapin (*Chrysolepis chrysophylla*), and bigleaf maple (*Acer macrophyllum*; Davis & Borchert 2006; Klein et al. 2015; Buck-Diaz et al. 2021; Vuln. Assessment Worksheets, pers. comm., 2022; CNPS 2023). These forests are found in a variety of settings, including riparian areas, coastal bluffs, inland ridges, steep north-facing slopes, and rocky outcrops (Vuln. Assessment Worksheets, pers. comm., 2022). Forest structure and composition can vary widely depending on moisture balance, disturbance history (e.g., fire), and site conditions (e.g., aspect, slope, soil properties), which create a mosaic of forest patches that result in high heterogeneity across the landscape (Bingham & Sawyer 1991; Spies et al. 2006; Sawyer 2007). As a result, these forests also support a diverse array of plant and wildlife species, including many endemics and unique vegetation communities (Sawyer 2007).

Fine-scale vegetation maps for San Mateo, Marin, and Sonoma Counties were used to identify the distribution of the *Pseudotsuga menziesii* – *Notholithocarpus densiflorus* / *Vaccinium ovatum* Association that represents mixed evergreen forests within the GGB region, where individual parcels must also contain 30–70% conifer and 30–70% hardwood cover (Tukman Geospatial et al. 2018). These occupy a total of 60,677 acres (Figure 1) of which 22% (13,577 acres) is protected, with the largest area of protected lands managed by The Conservation Fund – California (5,171 acres; Table 1).

An additional 175,902 acres were categorized within map classes that may represent degraded mixed evergreen forest with conifer or hardwood components of less than 30%; these include some areas of the *Pseudotsuga menziesii* – *Notholithocarpus densiflorus* / *Vaccinium ovatum* Association, as well as the *Arbutus menziesii* Alliance, *Pinus lambertiana* Alliance, *Pinus ponderosa* - *Pseudotsuga menziesii*

Alliance, *Quercus chrysolepis* (tree) Alliance, and *Umbellularia californica* Mapping Unit. These are interspersed with stands of cypress and closed-cone pines (e.g., *Pinus attenuata* Alliance, *Pinus muricata* – *Pinus radiata* Alliance), which were not included in the total acreage presented here.

Table 1. Total protected acres in the GGB region by land management agency, derived from fine scale vegetation maps for San Mateo, Marin, and Sonoma Counties (Tukman Geospatial et al. 2018).

Land Management Agency	Protected Acres
The Conservation Fund – California	5,171
California Department of Parks and Recreation	2,833
National Park Service – Point Reyes National Seashore	1,331
Sonoma County Agricultural Preservation and Open Space District	734
Other protected lands	592
Midpeninsula Regional Open Space District	512
San Francisco – Public Utilities Commission	448
United States Army Corps of Engineers	386
Marin Municipal Water District	347
Sonoma County Regional Parks Department	322
Audubon Canyon Ranch	246
United States Bureau of Land Management	187
Sonoma Land Trust	125
National Park Service – Golden Gate National Recreation Area	109
San Mateo County Parks and Recreation Department	104
Marin County Parks	86
Peninsula Open Space Trust	38
California State Lands Commission	8
TOTAL	13,577

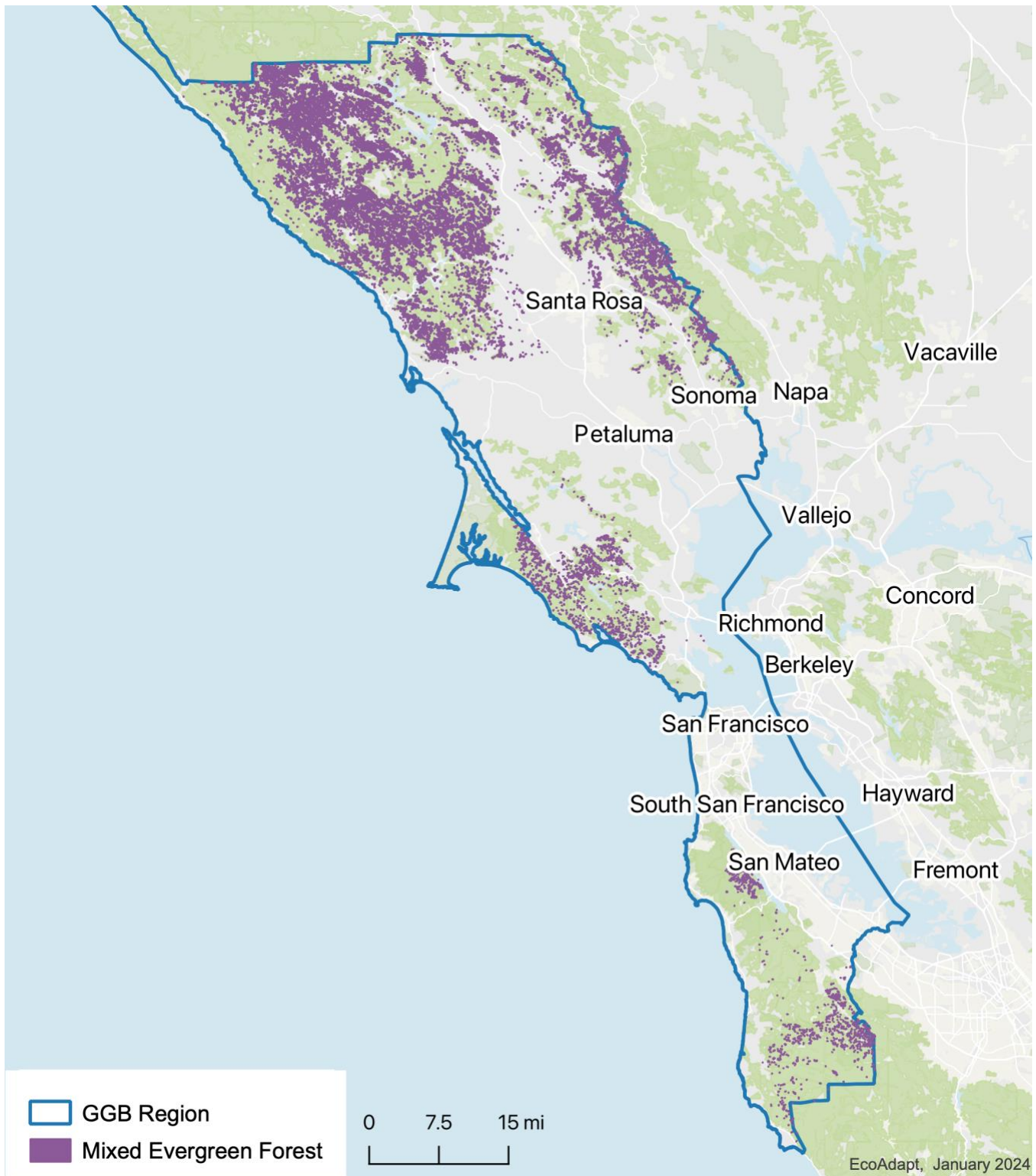


Figure 1. Distribution of vegetation map classes that likely represent mixed evergreen forests within the GGB region, derived from fine scale vegetation maps for San Mateo, Marin, and Sonoma Counties (Tukman Geospatial et al. 2018).

Ecosystem Vulnerability → Moderate (*moderate confidence*)

Vulnerability is evaluated by considering the ecosystem's sensitivity and exposure to various climate and non-climate stressors as well as the ecosystem's adaptive capacity (i.e., ability to cope with these stressors), and is given a ranking of low, moderate, or high. The confidence ranking represents confidence in the accuracy of the ranking based on available scientific knowledge, and is similarly ranked on a scale from low to high.

Summary of ecosystem vulnerability

Mixed evergreen forests are sensitive to changes in climate factors that increase water demand (e.g., air temperature) or decrease water availability (e.g., precipitation, drought). These changes are likely to alter patterns of tree growth and mortality, resulting in shifts in species composition, forest structure, and survival and regeneration. Changes in the frequency, timing, and/or intensity of disturbances (e.g., wildfire, disease, insect outbreaks, storms) may cause more extensive mortality, especially in stands where increased competition for soil moisture has reduced tree vigor. Non-climate stressors (e.g., fire exclusion, timber harvest, invasive plants, roads/highways/trails, and development) can exacerbate habitat sensitivity by reducing forest extent and altering forest structure, species composition, ecosystem functioning, and connectivity.

Mixed evergreen forests are widespread throughout much of the GGB region. However, fire exclusion, historical logging, and land-use conversion to development and agriculture have fragmented and degraded forests, reducing structural integrity and increasing vulnerability to disturbances such as uncharacteristically severe wildfires and drought. Resistance to climate stressors and altered disturbance regimes is supported by high landscape heterogeneity, and structural and species diversity within mixed evergreen forests in the region may allow shifts in composition towards species adapted to warmer, drier conditions. However, climate change may also slow forest recovery following disturbances, and large, severe disturbances have the potential to drive type conversion to non-forested vegetation types, especially in degraded areas. Management activities designed to increase forest resilience to climate change are likely to focus on promoting spatial heterogeneity and structural complexity as well as protecting forests from anthropogenic stressors and conserving areas that may serve as refugia.

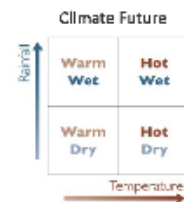
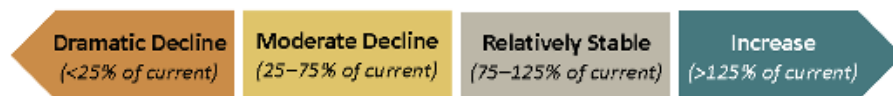
Sensitivity and Exposure → High (*high confidence*)

***Sensitivity** is a measure of whether and how an ecosystem is likely to be affected by a given change in climate factors, climate-driven changes in disturbance regimes, and non-climate stressors. By contrast, **exposure** is a measure of how much change in these factors an ecosystem is likely to experience. Sensitivity and exposure are combined here into one score representing both components of vulnerability, with high scores corresponding to increased vulnerability and low scores suggesting an ecosystem is less vulnerable.*

Modeling of climate-driven changes in the future distribution of several characteristic mixed evergreen forest species by Ackerly et al. (2015) found that the response of this group to climate change is expected to vary (Figure 2). For instance, California black oak, Oregon white oak, and canyon live oak are expected to decline in many landscape units, particularly under hotter or drier future scenarios. By contrast, Pacific madrone, interior live oak, and Douglas-fir are mostly projected to remain stable (except for some units where they may decline under hot/dry scenarios), while California bay laurel and coast live oak are largely expected to remain stable or expand. Species distribution modeling conducted by the Conservation Biology Institute for this project found that areas with climatic conditions expected to be suitable for Douglas-fir within the GGB region is projected to increase by 10–23% under the warm/high rainfall and warm/moderate rainfall scenarios, but contract by 53% under the hot/low rainfall scenario, shifts that are most closely associated with projected changes in winter precipitation (Figure 3; Syphard & Rustigian-Romsos 2024). The distribution of this species within the region is already extensive, so areas of expansion under high- and moderate-precipitation scenarios are concentrated in the Russian River Valley and Sonoma Valley area where Douglas-fir is not currently found. Under the low precipitation scenario, contractions in suitable conditions would be particularly likely in the southern portion of the region. The scientific literature suggests that even in areas where overall conditions become less suitable, microrefugia may occur in shadier areas and where cool air predictably pools such as on north-facing slopes and in valley bottoms, steep canyons, and sinks and basins (Dobrowski 2011; Olson et al. 2012).

Modeled Changes in Vegetation Distribution

Direction and magnitude of change in vegetation cover by 2050



Douglas-fir (*Pseudotsuga menziesii*)



Pacific Madrone (*Arbutus menziesii*)



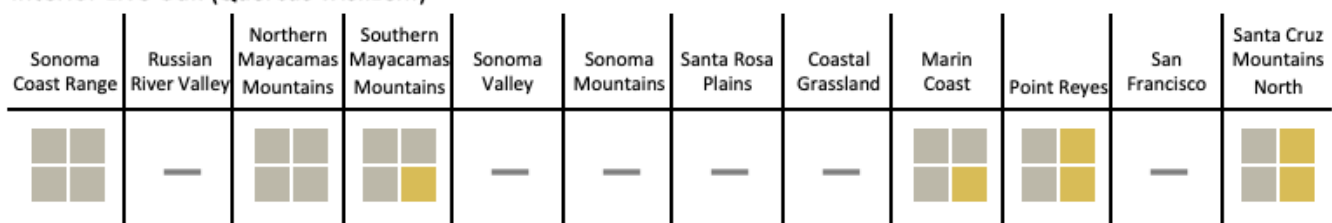
California Bay Laurel (*Umbellularia californica*)



Canyon Live Oak (*Quercus chrysolepis*)



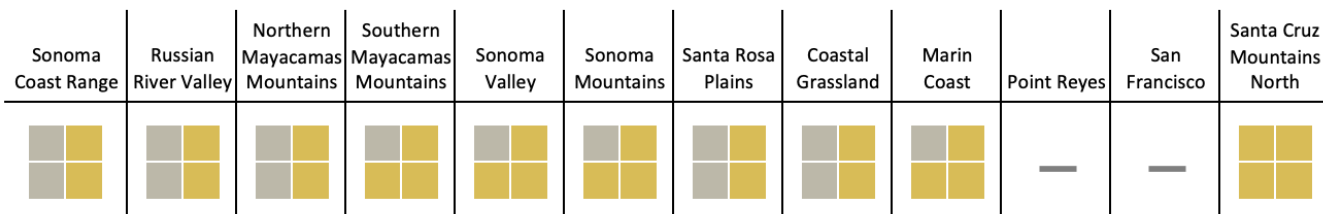
Interior Live Oak (*Quercus wislizeni*)



Coast Live Oak (*Quercus agrifolia*)



California black oak (*Quercus kelloggii*)



Oregon white oak (*Quercus garryana*)

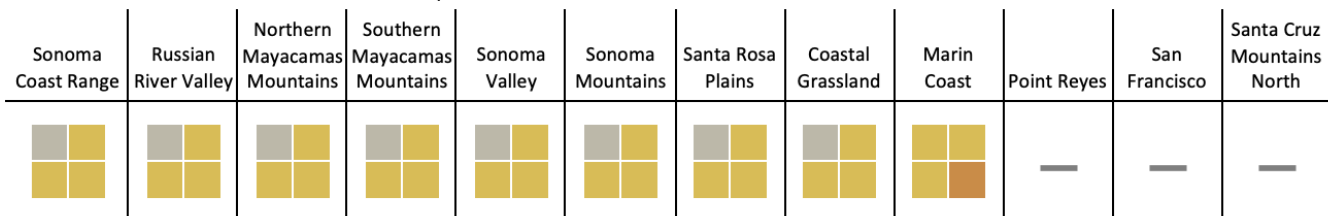


Figure 2. Projected trends in vegetation distribution by mid-century (~2050) within landscape units overlapping the GGB region, based on results from Ackerly et al. (2015). The four squares refer to a range of possible climate futures that vary with respect to temperature and precipitation, with the top and bottom squares representing wetter and drier scenarios, respectively, and the left and right squares representing scenarios projecting average annual temperature increases of greater than and less than 4.5°C, respectively. The color of the squares indicates the direction and magnitude of change in vegetation cover by 2050, with orange representing dramatic declines (less than 25% of current cover present), yellow representing moderate declines (25–75% of current), gray representing relatively stable cover (75–125% of current), and green represents increases (more than 125% of current).

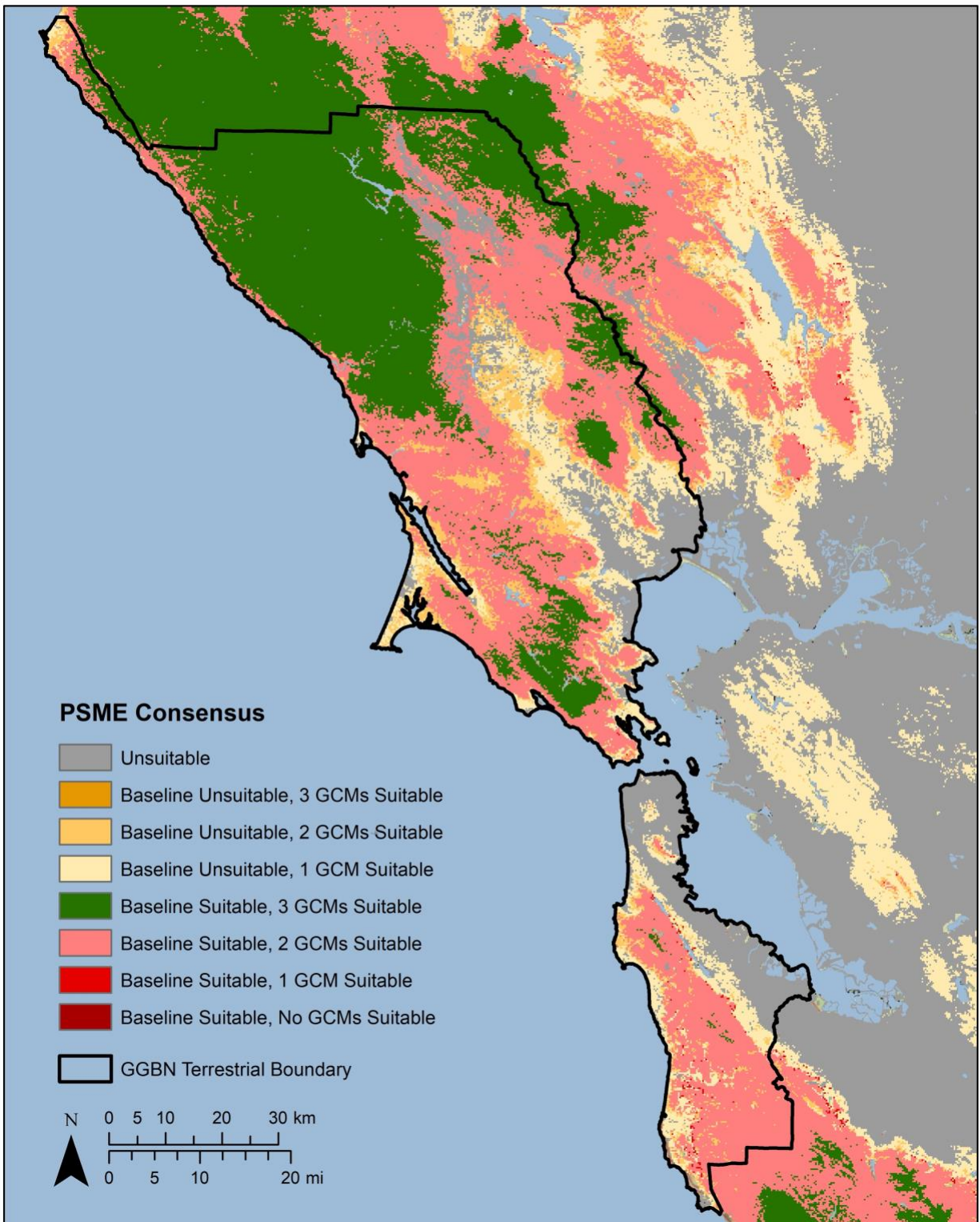


Figure 3. Future climatic suitability for Douglas-fir (PSME) for an end-of-century time frame (2070–2099 compared to 1981–2010). Species distribution model compares baseline (current distribution) to three global climate models (GCMs) under the RCP 8.5 emissions scenario. GCMs included are CNRM-CM5 (warm/high rainfall), CCSM4 (warm/moderate rainfall), and MIROC-ESM (hot/low rainfall), all using the RCP 8.5 emissions scenario.

Sensitivity and future exposure to climate factors → High (*high confidence*)

- **Changes in precipitation patterns** (e.g., amount and/or timing) and **soil moisture** are likely to alter tree growth, recruitment, and mortality in mixed evergreen forests (van Mantgem et al. 2009; Allen et al. 2010; Ackerly et al. 2015; Dobrowski et al. 2015), potentially driving longer-term shifts in forest structure and species composition (Stephenson 1998; Lenihan et al. 2008; Lutz et al. 2010; Chmura et al. 2011; Dobrowski et al. 2015). Increases in water stress as a result of longer, drier summers and/or overall reductions in precipitation would be likely to limit tree growth and increase mortality, particularly on drier sites and for species already existing at the southern edge of their range within the GGB region (e.g., Douglas-fir, coast redwood; van Mantgem et al. 2009; Lutz et al. 2010; Restaino et al. 2016; Dagley et al. 2023). Increased water stress is associated with enhanced vulnerability to injury and mortality from stressors such as drought (Young et al. 2017), insects (Fettig et al. 2007; Kolb et al. 2016), disease (Millar & Stephenson 2015; Kolb et al. 2016), and wildfire (van Mantgem et al. 2013). Climate-driven changes in tree recruitment, including post-fire regeneration, could also result in shifts in species composition towards drought-tolerant hardwoods and shrubs, particularly on drier sites (Lenihan et al. 2008; Welch et al. 2016).

Increases in precipitation would likely enhance forest productivity to some degree (North et al. 2016), although this also has the potential to increase wildfire risk due to greater availability of potential fuels (e.g., invasive grasses, brush, and other vegetation) during subsequent dry years (Williams et al. 2019). Increases in winter rainfall would likely also drive higher spore production and transmission of the pathogen that causes sudden oak death (*Phytophthora ramorum*), increasing infection risk and associated mortality (Davidson et al. 2005; DiLeo et al. 2014). By contrast, dry conditions and low soil moisture have a strong limiting effect on sudden oak death (Venette & Cohen 2006), and reduced duration and magnitude of winter precipitation could limit the spread of this disease (Kliejunas 2011)

- **Increased drought** may cause significant tree mortality (Allen et al. 2010, 2015; Anderegg et al. 2013; McDowell & Allen 2015; Young et al. 2017; Brodrick et al. 2019), especially in large trees and in dense stands where competition for soil moisture is high (Allen et al. 2010; McDowell & Allen 2015; Young et al. 2017; Schmitt et al. 2020). Seedlings are more sensitive to drought compared to mature trees, and reduced recruitment during periods of drought could contribute to shifts in composition based on variable species responses (Dobrowski et al. 2015). Generally, species with intermediate drought tolerance (e.g., Pacific madrone) show fewer projected recruitment declines compared to those at the high and low ends of the spectrum (Dobrowski et al. 2015). Mortality rates typically increase as drought progresses over multiple years (Young et al. 2017), and the effects of severe drought (e.g., growth declines, high tree mortality rates) can persist for several years after the drought is over (Anderegg et al. 2015; Brodrick et al. 2019). Under future climate conditions, prolonged and/or severe droughts may cause large-scale forest dieback (Allen et al. 2015; McDowell & Allen 2015; Millar & Stephenson

2015), with higher rates of mortality occurring where trees have already been stressed by climate-driven increases in wildfire, insect outbreaks, disease, and previous droughts (Allen et al. 2010; van Mantgem et al. 2013; McDowell & Allen 2015; Millar & Stephenson 2015; Kolb et al. 2016; Young et al. 2017).

- **Warmer air temperatures** are likely to enhance water stress within mixed evergreen forests due to increased evaporative demand (Thorne et al. 2015), which is associated with growth declines, tree mortality, and shifts in species composition and forest distribution (Lenihan et al. 2008; van Mantgem et al. 2009; Ackerly et al. 2015; Restaino et al. 2016). However, warmer temperatures may also increase productivity and seedling recruitment in some hardwood species (e.g., Pacific madrone, California bay, coast live oak), enhancing competition with conifers and potentially contributing to shifts in species composition towards a greater proportion of hardwoods (Lenihan et al. 2008; Dobrowski et al. 2015). Warmer temperatures have the potential to contribute to the expansion of diseases such as sudden oak death (Venette 2009), changes in the timing and/or synchronicity of bark beetle life cycles (Bentz et al. 2010), and increased vulnerability of trees to mortality from stressors such as drought (Millar & Stephenson 2015).
- **Increased heat waves** are likely to be associated with increases in fire size, rate of spread and severity (Sharples 2009; Estes et al. 2017), driving more extreme fire conditions and corresponding impacts on mixed evergreen forests. This is particularly likely to occur when the high pressure systems associated with late summer and fall heat waves also produce warm, dry east winds (Schroeder et al. 1964).
- Precipitation-driven **changes in stream flow regimes** are likely to result in higher spring peak flows and longer periods of summer low flows that increase water stress during the dry season (Clow 2010; Flint et al. 2023). The resulting declines in fuel moisture will increase fire potential in forests where fuels are not limiting (Gergel et al. 2017).

Sensitivity and future exposure to climate-driven changes in disturbances → High (*moderate confidence*)

- Mixed evergreen forests are dependent on mixed-severity fire regimes to maintain their heterogeneous stand structure and composition (Hunter & Parker 1993; Stephens & Fry 2005; Donato et al. 2009). However, **climate-driven increases in the frequency and/or severity of wildfires** are likely to increase tree mortality and cause substantial modifications in forest structure and composition by favoring post-fire dominance of sprouting hardwoods and shrubs (Stuart & Stephens 2006; Cocking et al. 2012; North et al. 2016; Welch et al. 2016). These changes are particularly likely within the interior of larger high-severity patches, where conifer recovery may be delayed due to lack of seed sources in combination with warmer, drier conditions that limit seedling establishment (Tepley et al. 2017; Serra-Diaz et al. 2018; Davis et al. 2023). Repeated high-severity fire can also alter forest structure and prevent the

development of later-successional stages by killing seedlings, sprouting stems, and saplings before they have matured and developed thick bark and other fire-resistant characteristics (Pausas 2015; Hammett et al. 2017; Nemens et al. 2018). However, there is some evidence that complex early- to mid-successional mixed evergreen stands can recover rapidly post-fire and support diverse plant and bird communities (Donato et al. 2009; Fontaine et al. 2009), suggesting that forest heterogeneity is a key factor in resilience to high-severity fire. Increased fire frequency, particularly at the low- to moderate- intensities to which most species are adapted, also has the potential to support the persistence of fire-dependent species such as Sargent cypress (*Hesperocyparis sargentii*) and bishop pine (*Pinus muricata*; Merriam & Rentz 2010; Reilly et al. 2019; Vuln. Assessment Worksheets, pers. comm., 2022). However, fires that occur too frequently may kill trees before they mature and produce cones, resulting in stand extirpation (Enright et al. 2014, 2015; Reilly et al. 2019; McNamara et al. 2019).

- Increases in disease** may cause more extensive tree mortality as changes in temperature, moisture, and disturbance regimes impact pathogen production and transmission as well as tree defenses, host susceptibility, and community interactions (Kliejunas 2011; Sturrock et al. 2011; Contreras-Cornejo et al. 2023). Within the GGB region, sudden oak death (caused by the introduced pathogen *Phytophthora ramorum*) within mixed evergreen forests is of great concern, particularly in the western portion of the study area as well as some inland locations (e.g., Jack London State Historic Park in the Sonoma Valley; Vuln. Assessment Worksheets, pers. comm., 2022). Sudden oak death is primarily transmitted by California bay (Rizzo & Garbelotto 2003; Cobb et al. 2010) and causes high rates of injury and mortality in tanoak and several species of true oaks (e.g., coast live oak), particularly for large trees (McPherson et al. 2010; Cobb et al. 2012; Haas et al. 2016). Beetle attacks in infected trees can speed mortality, reducing life expectancy by 65–70% (McPherson et al. 2010). Because the impacts of sudden oak death are species-specific, patterns of mortality can significantly alter forest structure and species composition (Cobb et al. 2012; Metz et al. 2012; Haas et al. 2016). Tanoak has already been eliminated as a co-dominant species on many sites within the region (Vuln. Assessment Worksheets, pers. comm., 2022) and significant further losses of tanoak, especially larger individuals, are likely to occur (McPherson et al. 2010; Cobb et al. 2012). Over time, this has the potential to shift overstory composition towards species with lower susceptibility to infection (Cobb et al. 2010), although impacted tanoak trees often continue to sprout and form dense thickets in the understory (Cobb et al. 2012; Metz et al. 2012). High rates of tree mortality and resulting shifts in species composition and stand structure may also change patterns of fuel composition and availability, potentially altering fire behavior (Metz et al. 2011, 2017; Forrestel et al. 2015; Varner et al. 2017).

Changing climate conditions may alter patterns of spore production, disease transmission, susceptibility, and mortality in forests impacted by sudden oak death (Meentemeyer et al. 2004; Venette 2009; Kliejunas 2011; Sturrock et al. 2011). For instance, warmer winter

temperatures and increased winter and spring precipitation are likely to enhance spore production and increase infection risk (Davidson et al. 2008; Kliejunas 2011; Meentemeyer et al. 2011; DiLeo et al. 2014; Haas et al. 2016). Conversely, drier summer conditions could reduce disease prevalence by limiting growth of *P. ramorum* (Davidson et al. 2005; Venette & Cohen 2006), particularly along the leading eastern edge of areas impacted by sudden oak death (Vuln. Assessment Worksheets, pers. comm., 2022).

- Climate-driven **increases in insect outbreaks** may cause significant tree mortality, with the potential to alter forest composition and structure (Raffa et al. 2008; Hicke et al. 2016). These impacts may be more likely to occur where the abundance of host species is high and/or in dense, homogenous stands where trees already stressed from competition are more vulnerable to attack (Fettig et al. 2007, 2013; Bentz et al. 2010). Insect-related tree mortality also has significant impacts on fuel structure and availability, though existing studies draw varying conclusions about whether this leads to changes in fire behavior or severity (Hicke et al. 2012; Harvey et al. 2013; Meigs et al. 2015; Hart et al. 2015; Stephens et al. 2018) and researchers are continuing to investigate this question across ecosystems and climate regimes (Fettig et al. 2022). It is likely that future climate changes will impact the prevalence and severity of insect outbreaks, both directly by altering insect development rates and survival, and indirectly by impacting tree defenses, host susceptibility, and community interactions (Raffa et al. 2008; Bentz et al. 2010; Weed et al. 2013; Kolb et al. 2016; Agne et al. 2018). For instance, warming temperatures are contributing to earlier insect emergence, more completed life cycles within a season, and expanding distributions for species typically restricted to more southern ranges (Bentz et al. 2010; North et al. 2016). Drought stress is also known to increase the risk of large-scale insect outbreaks (Bentz et al. 2010; Weed et al. 2013; Kolb et al. 2016); conversely, injury from insect attacks can also increase tree vulnerability to drought stress and associated mortality (Kolb et al. 2016).
- **Increased frequency and/or severity of storms** may cause more frequent tree mortality due to windthrow and landslides, particularly in recently-burned areas (Hunter & Parker 1993). Dense stands are often more susceptible to these impacts, as trees may be less healthy due to competition for resources such as soil moisture (Vuln. Assessment Worksheets, pers. comm., 2022).

Sensitivity and current exposure to non-climate stressors → High (*high confidence*)

Non-climate stressors can exacerbate ecosystem sensitivity to changes in climate factors and disturbance regimes, and/or can be exacerbated by these changes.

- **Fire exclusion and suppression** has drastically altered historical wildfire regimes, increasing fire return intervals within central California mixed evergreen forests to over 150 years compared to 30–135 years prior to Euro-American settlement in the absence of tribal burning, and likely closer to 8–12 years where stands were maintained by frequent cultural burning (Stephens &

Fry 2005; Davis & Borchert 2006). Reductions in fire frequency due to fire exclusion and suppression has resulted in dense stands, particularly where logging also reduced the number of large trees and increased the density of small trees and understory shrubs (Odion et al. 2014; McIntyre et al. 2015). This shift in stand structure has increased fuel loading, which enhances the risk that fires will be severe when they do occur (Lorimer et al. 2009; Steel et al. 2015), as well as susceptibility to pathogens (Meentemeyer et al. 2008), insect outbreaks (Fettig et al. 2007), and storm damage (Vuln. Assessment Worksheets, pers. comm., 2022). Shifts in species composition have also occurred in some areas, as shade-tolerant trees and shrubs in the forest understory increase stem density and slower-growing hardwoods such as Pacific madrone decline (Hunter 1997; Stuart & Stephens 2006; Vuln. Assessment Worksheets, pers. comm., 2022).

- **Timber harvest** has resulted in the loss and fragmentation of many old-growth mixed evergreen forests in the GGB region, particularly in redwood-dominated stands (Stephens & Fry 2005; Baumgarten et al. 2021). Historical logging followed by decades of fire suppression has resulted in higher stem densities and lower structural diversity in second-growth forests, which reduces forest heterogeneity at the landscape scale (Spies et al. 2006; McIntyre et al. 2015). These dense forests experience lower growth rates, increased mortality, and greater vulnerability to insects, disease, drought, and severe wildfire (Lorimer et al. 2009; Zald & Dunn 2018), significantly increasing their vulnerability to future climate changes that may exacerbate those impacts.
- **Invasive plants** compete with native vegetation and alter soil properties, affecting forest structure, species composition, and ecosystem processes (Dukes & Mooney 2004; Olimpi et al. 2016). Within the GGB region, woody invasives such as French broom (*Genista monspessulana*) reduce biodiversity and serve as ladder fuels, increasing vulnerability to intense wildfires (Alexander & D'Antonio 2003; Mandle et al. 2011). As mentioned above, **invasive pathogens** such as *P. ramorum* and *P. cinnamomi* can also have significant impacts on the ecosystem, including as a driver of altered fire frequency and behavior (e.g., Forrestel et al. 2015), and their prevalence is likely to be influenced by changes in precipitation and other climate factors (Kliejunas 2011; Sturrock et al. 2011; Contreras-Cornejo et al. 2023).
- **Roads, highways, and recreational trails** increase habitat fragmentation and alter ecosystem dynamics in mixed evergreen forests (Trombulak & Frissell 2000; Coffin 2007). For example, transportation corridors contribute to the introduction and spread of invasive plants (Trombulak & Frissell 2000; Coffin 2007) and are associated with increased fire ignitions (Syphard & Keeley 2015). Roads and trails also provide enhanced opportunities for the spread of sudden oak death, both because of greater air movement that increases spore dispersal and because spores within the soil can be transported on vehicles (e.g., mud in tire treads), footwear, and equipment (Cushman & Meentemeyer 2006a, 2006b).

- **Residential/commercial development** has resulted in the loss and fragmentation of forests within the region, particularly in and around the growing wildland-urban interface (Vuln. Assessment Worksheets, pers. comm., 2022). However, mixed evergreen forests have experienced relatively fewer impacts of development compared to other ecosystems (e.g., coastal scrub, coastal prairie) due to their distribution within more remote areas farther from population centers.

Adaptive Capacity → Moderate (moderate confidence)

***Adaptive capacity** is the ability of an ecosystem to respond to or cope with climate change impacts with minimal disruption. High adaptive capacity corresponds to lower overall climate change vulnerability, while low adaptive capacity means that the ecosystem will be less likely to cope with the adverse effects of climate change, thus increasing the vulnerability of the ecosystem.*

Ecosystem extent, integrity, and continuity → High (moderate confidence)

Mixed evergreen forests are widespread throughout the GGB region and the state. The ecosystem extends north into southwestern Oregon (Davis & Borchert 2006), with distribution largely driven by temperature and water availability (Vuln. Assessment Worksheets, pers. comm., 2022). Historically, this forest type expanded within the region due to a combination of natural succession, cessation of indigenous cultural burning and active fire suppression following Euro-American settlement, favorable climate conditions (particularly periods of increased precipitation), and planting of species such as Douglas-fir (Baumgarten et al. 2021). For instance, within the Peninsula Watershed, a 26,000-acre area within San Mateo County, conifer forests (a grouping that includes mixed evergreen) expanded by 78–91% between roughly 1930 and 2000 (Baumgarten et al. 2021). However, land-use conversion, historical logging and fire exclusion, invasive plants, and other stressors have ultimately resulted in at least some level of degradation in many mixed evergreen stands within the region (Vuln. Assessment Worksheets, pers. comm., 2022), reducing ecosystem integrity and increasing vulnerability to disturbances such as large, uncharacteristically-severe wildfires, intense drought, pests, and pathogens (Millar & Stephenson 2015; Young et al. 2017). These factors can have particularly significant impacts on persistence of stands dominated by less widely-distributed species such as Sargent cypress, canyon live oak, Pacific madrone, and bishop pine (Vuln. Assessment Worksheets, pers. comm., 2022). Impacts on stands dominated by less-common species can occur through direct removal as well as lack of disturbance (or too-frequent disturbances), changes in site conditions that reduce suitability, or fragmentation that impacts seed dispersal and regeneration (Baumgarten et al. 2021; Vuln. Assessment Worksheets, pers. comm., 2022).

Ecosystem diversity → Moderate (moderate confidence)

Mixed evergreen forests in the GGB region occupy topographically diverse areas with varied site conditions (e.g., substrate, water balance, disturbance history; Vuln. Assessment Worksheets, pers.

comm., 2022). These factors contribute to high species diversity and significant phenotypic and genetic variability across the landscape (Vuln. Assessment Worksheets, pers. comm., 2022), which may allow shifts in forest composition towards species adapted to warmer, drier conditions (Schierenbeck 2017). Stands with high species diversity also tend to have lower risk of infection with sudden oak death due to reduced host density (Cobb et al. 2012; Haas et al. 2016; Gaydos et al. 2017). However, some species may be sensitive to climate changes, particularly those that drive altered fire regimes, and these components may be lost where fire becomes too frequent or repeated high-severity fires occur (e.g., Enright et al. 2014, 2015).

In addition to harboring high plant diversity, mixed evergreen forests host a number of threatened and endangered wildlife species, such as the northern spotted owl (*Strix occidentalis caurina*; Vuln. Assessment Worksheets, pers. comm., 2022).

Resistance and recovery → Moderate (moderate confidence)

Resistance to climate stressors and altered disturbance regimes in mixed evergreen forests is supported by high landscape-scale heterogeneity, which provides varied microsites that act as refugia from thermal stress, increasing water deficits, and wildfire (Frey et al. 2016; Tepley et al. 2017; Ackerly et al. 2020). Many component species within mixed evergreen forests are characterized by tolerance to multiple stressors (e.g., shade, drought, fire), and several of these species are projected to see increased recruitment under future climate conditions, suggesting greater resilience within this forest type compared to many others (Dobrowski et al. 2015). For instance, madrone may experience topkill following fire, but resprouts readily and has good germination rates in burned areas (Reeves 2007). However, other species (e.g., Douglas-fir) are less resistant to drought or other stressors, and recovery can be significantly delayed in stands impacted by invasive weeds, sudden oak death, or other factors that reduce health and integrity (Spies et al. 2006; Vuln. Assessment Worksheets, pers. comm., 2022). Dense stands of trees are also generally more stressed and show reduced resistance to and recovery from drought and other disturbances (Bréda et al. 2006; Schmitt et al. 2020). Degraded areas such as these are at greater risk of significant shifts in species composition and possible type conversion to shrub-dominated vegetation following high-severity fire, particularly as warmer, drier conditions continue to alter post-fire recovery rates and successional patterns (Lenihan et al. 2008; Welch et al. 2016; Tepley et al. 2017; Davis et al. 2023).

Management potential → Moderate (moderate confidence)

Mixed evergreen forests in the GGB region are popular for recreational use and are highly valued for their beauty and wildlife viewing opportunities, particularly those with a significant redwood component (Vuln. Assessment Worksheets, pers. comm., 2022). Mixed evergreen forests are also of critical importance to area tribes, who have carefully managed tanoak stands and other culturally-valued species for food, medicine, and other purposes for centuries (Anderson 2005; Bowcutt 2013). Both the public and the broader society are becoming increasingly aware of the impacts that climate

change and related stressors such as the introduced pathogen sudden oak death are having on mixed evergreen forests, as well as the benefits these forests can provide in terms of cool microclimates, carbon storage, and other ecosystem services (Ellison et al. 2017; Vuln. Assessment Worksheets, pers. comm., 2022). However, despite multiple stakeholder groups that are vocal and involved in forest conservation within the region, the public remain strong proponents of the status quo and are often suspicious of active management strategies (Vuln. Assessment Worksheets, pers. comm., 2022).

Strategically placed, multi-benefit forest treatments can be very effective for increasing the health and resilience of mixed evergreen forests, but these usually occur at small scales (Dagley et al. 2018, 2023; Spies et al. 2018). Managing this ecosystem at larger scales is much more difficult, in part because it often occurs on steep terrain that makes access challenging (Vuln. Assessment Worksheets, pers. comm., 2022). Changing climate conditions are likely to make management of mixed evergreen forests even more difficult and complex, particularly at the landscape scale, due to the increased potential for stressed forests to experience significant shifts in species composition or large-scale dieback (McIntyre et al. 2015; Tepley et al. 2017; Young et al. 2017). Active management strategies focused on reducing forest density (Dagley et al. 2018, 2023), reintroducing fire onto the landscape (Jewell & Vilsack 2014; Hessburg et al. 2016), and supporting forest regeneration (Welch et al. 2016; Davis et al. 2023) are likely to remain critical, especially in forests that have been degraded or are experiencing stress due to climate change and other anthropogenic factors. These strategies are designed to enhance forest resilience by increasing spatial heterogeneity and structural complexity, which maintains biodiversity – including sensitive species – and reduces vulnerability to large-scale disturbances such as uncharacteristically-severe wildfire, insect outbreaks, and disease (Spies et al. 2006; Jewell & Vilsack 2014; Hessburg et al. 2016; Young et al. 2017; Dagley et al. 2018). For instance, reducing forest density through thinning and prescribed fire is associated with increased tree growth and vigor, and encourages the development of larger, more fire-resistant trees within mature, structurally-diverse stands (Franklin et al. 2002; Metlen et al. 2017; Spies et al. 2018; Dagley et al. 2023). However, the amount of acreage that can be treated each year is small compared to the full extent of mixed evergreen forests in the GGB region, and continued treatment (i.e., through regular use of prescribed fire or other means) is often necessary. Resources for protection and management may need to be concentrated first in areas that are likely to be refugia, including late-successional forests and complex mid- and early-seral stands with high structural diversity, as well as sites that increase landscape connectivity (Franklin & Johnson 2012; DellaSala & Hanson 2015; Spies et al. 2018). Additionally, implementation of prescribed fire can be challenging due to regulatory and administrative hurdles (Clark et al. 2021; Vuln. Assessment Worksheets, pers. comm., 2022). Nevertheless, reintroducing frequent fire into these ecosystems remains a key tool for increasing adaptive capacity, and numerous projects within the region are highlighting mechanisms to accomplish this, including collaboration with local tribes to implement cultural burning practices in accordance with traditional ecological knowledge (TEK) and tribal customs (Metlen et al. 2017; USDA Forest Service 2018; Clark et al. 2021).

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Literature Cited

- Ackerly DD, Cornwell WK, Weiss SB, Flint LE, Flint AL. 2015. A geographic mosaic of climate change impacts on terrestrial vegetation: Which areas are most at risk? *PLoS ONE* **10**:e0130629.
- Ackerly DD, Kling MM, Clark ML, Papper P, Oldfather MF, Flint AL, Flint LE. 2020. Topoclimate, refugia, and biotic responses to climate change. *Frontiers in Ecology and the Environment* **18**:288–297.
- Agne MC, Beedlow PA, Shaw DC, Woodruff DR, Lee EH, Cline SP, Comeleo RL. 2018. Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. *Forest Ecology and Management* **409**:317–332.
- Alexander JM, D’Antonio CM. 2003. Seed bank dynamics of French broom in coastal California grasslands: Effects of stand age and prescribed burning on control and restoration. *Restoration Ecology* **11**:185–197.
- Allen CD et al. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* **259**:660–684.
- Allen CD, Breshears DD, McDowell NG. 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere* **6**:1–55.
- Anderegg WRL et al. 2015. Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science* **349**:528–532.
- Anderegg WRL, Kane JM, Anderegg LDL. 2013. Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change* **3**:30–36.
- Anderson MK. 2005. *Tending the wild: Native American knowledge and the management of California’s natural resources*. University of California Press, Berkeley, CA.
- Baumgarten SA, Hagerty S, Vaughn LS, Spotswood E, Grossinger RM, Beller EE, Salomon M, Clark E, Stoneburner L. 2021. Peninsula Watershed historical ecology study. SFEI Contribution No. 1029. San Francisco Estuary Institute, Richmond, CA. Available from <https://www.sfei.org/documents/peninsula-watershed-historical-ecology-study> (accessed March 28, 2023).
- Bentz BJ, Regniere J, Fettig CJ, Hansen EM, Hayes JL, Hicke JA, Kelsey RG, Negrón JF, Seybold SJ. 2010. Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. *BioScience* **60**:602–613.
- Bingham BB, Sawyer JO. 1991. Distinctive features and definitions of young, mature, and old-growth Douglas-fir/hardwood forests. Pages 363–377 in Ruggiero LF, Aubry KB, Carey AB, Huff MH, editors. *Wildlife and vegetation of unmanaged Douglas-fir forests*. Gen. Tech. Rep. PNW-GTR-285. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Bowcutt F. 2013. Tanoak landscapes: Tending a Native American nut tree. *Madroño* **60**:64–86.

- Bréda N, Huc R, Granier A, Dreyer E. 2006. Temperate forest trees and stands under severe drought: A review of ecophysiological responses, adaptation processes and long-term consequences. *Annals of Forest Science* **63**:625–644.
- Brodrick PG, Anderegg LDL, Asner GP. 2019. Forest drought resistance at large geographic scales. *Geophysical Research Letters* **46**:2752–2760.
- Buck-Diaz J, Sikes K, Evans JM. 2021. Vegetation classification of alliances and associations in Marin County, California. California Native Plant Society, Vegetation Program, Sacramento, CA.
- Chmura DJ, Anderson PD, Howe GT, Harrington C a, Halofsky JE, Peterson DL, Shaw DC, Brad St. Clair J. 2011. Forest responses to climate change in the northwestern United States: Ecophysiological foundations for adaptive management. *Forest Ecology and Management* **261**:1121–1142.
- Clark SA, Miller A, Hankins DL. 2021. Good Fire: Current barriers to the expansion of cultural burning and prescribed fire in California and recommended solutions. Karuk Tribe, Happy Camp, CA. Available from <https://karuktribeclimatechangeprojects.com/good-fire/> (accessed January 13, 2022).
- Clow DW. 2010. Changes in the timing of snowmelt and streamflow in Colorado: A response to recent warming. *Journal of Climate* **23**:2293–2306.
- CNPS. 2023. A manual of California vegetation, online edition. California Native Plant Society Press. Available from <http://www.cnps.org/cnps/vegetation/> (accessed May 25, 2023).
- Cobb RC, Filipe JAN, Meentemeyer RK, Gilligan CA, Rizzo DM. 2012. Ecosystem transformation by emerging infectious disease: Loss of large tanoak from California forests. *Journal of Ecology* **100**:712–722.
- Cobb RC, Meentemeyer RK, Rizzo DM. 2010. Apparent competition in canopy trees determined by pathogen transmission rather than susceptibility. *Ecology* **91**:327–333.
- Cocking MI, Varner JM, Sherriff RL. 2012. California black oak responses to fire severity and native conifer encroachment in the Klamath Mountains. *Forest Ecology and Management* **270**:25–34.
- Coffin AW. 2007. From roadkill to road ecology: A review of the ecological effects of roads. *Journal of Transport Geography* **15**:396–406.
- Contreras-Cornejo HA, Larsen J, Fernández-Pavía SP, Oyama K. 2023. Climate change, a booster of disease outbreaks by the plant pathogen *Phytophthora* in oak forests. *Rhizosphere* **27**:100719.
- Cushman JH, Meentemeyer RK. 2006a. Multi-scale patterns of human activity and the incidence of an exotic forest pathogen. *Journal of Ecology* **96**:766–776.
- Cushman JH, Meentemeyer RK. 2006b. The importance of humans in the dispersal and spread of *Phytophthora ramorum* at local, landscape, and regional scales. Pages 161–163 in Frankel SJ, Shea PJ, Haverly MI, editors. Proceedings of the sudden oak death second science symposium: The state of our knowledge. Gen. Tech. Rep. PSW-GTR-196. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
- Dagley CM, Berrill J-P, Fraver S. 2023. Forest restoration mitigates drought vulnerability of coast Douglas-fir in a Mediterranean climate. *Canadian Journal of Forest Research* **53**:210–216.
- Dagley CM, Berrill J-P, Leonard LP, Kim YG. 2018. Restoration thinning enhances growth and diversity in mixed redwood/Douglas-fir stands in northern California, U.S.A. *Restoration Ecology* **26**:1170–1179.
- Davidson JM, Patterson HA, Rizzo DM. 2008. Sources of inoculum for *Phytophthora ramorum* in a redwood forest. *Phytopathology* **98**:860–866.
- Davidson JM, Wickland AC, Patterson HA, Falk KR, Rizzo DM. 2005. Transmission of *Phytophthora ramorum* in mixed-evergreen forest in California. *Phytopathology* **95**:587–596.

- Davis FW, Borchert MI. 2006. Central Coast bioregion. Pages 321–349 in Sugihara NG, van Wagtenonk JW, Fites-Kaufmann J, Shaffer KE, Thode AE, editors. Fire in California’s ecosystems. University of California Press, Berkeley, CA.
- Davis KT et al. 2023. Reduced fire severity offers near-term buffer to climate-driven declines in conifer resilience across the western United States. *Proceedings of the National Academy of Sciences* **120**:e2208120120.
- DellaSala DA, Hanson CT. 2015. The ecological importance of mixed-severity fires: Nature’s phoenix. Elsevier, Amsterdam.
- DiLeo MV, Bostock RM, Rizzo DM. 2014. Microclimate impacts survival and prevalence of *Phytophthora ramorum* in *Umbellularia californica*, a key reservoir host of Sudden Oak Death in northern California forests. *PLoS ONE* **9**:e98195.
- Dobrowski SZ. 2011. A climatic basis for microrefugia: The influence of terrain on climate. *Global Change Biology* **17**:1022–1035.
- Dobrowski SZ, Swanson AK, Abatzoglou JT, Holden ZA, Safford HD, Schwartz MK, Gavin DG. 2015. Forest structure and species traits mediate projected recruitment declines in western US tree species. *Global Ecology and Biogeography* **24**:917–927.
- Donato DC, Fontaine JB, Robinson WD, Kauffman JB, Law BE. 2009. Vegetation response to a short interval between high-severity wildfires in a mixed-evergreen forest. *Journal of Ecology* **97**:142–154.
- Dukes JS, Mooney HA. 2004. Disruption of ecosystem processes in western North America by invasive species. *Revista Chilena de Historia Natural* **77**:411–437.
- Ellison D et al. 2017. Trees, forests and water: Cool insights for a hot world. *Global Environmental Change* **43**:51–61.
- Enright NJ, Fontaine JB, Bowman DMJS, Bradstock RA, Williams RJ. 2015. Interval squeeze: Altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment* **13**:265–272.
- Enright NJ, Fontaine JB, Lamont BB, Miller BP, Westcott VC. 2014. Resistance and resilience to changing climate and fire regime depend on plant functional traits. *Journal of Ecology* **102**:1572–1581.
- Estes BL, Knapp EE, Skinner CN, Miller JD, Preisler HK. 2017. Factors influencing fire severity under moderate burning conditions in the Klamath Mountains, northern California, USA. *Ecosphere* **8**:e01794.
- Fettig CJ, Klepzig KD, Billings RF, Munson AS, Nebeker TE, Negrón JF, Nowak JT. 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. *Forest Ecology and Management* **238**:24–53.
- Fettig CJ, Reid ML, Bentz BJ, Sevanto S, Spittlehouse DL, Wang T. 2013. Changing climates, changing forests: A western North American perspective. *Journal of Forestry* **111**:214–228.
- Fettig CJ, Runyon JB, Homicz CS, James PMA, Ulyshen MD. 2022. Fire and insect interactions in North American forests. *Current Forestry Reports* **8**:301–316.
- Flint LE, Flint AL, Stern MA. 2023. The Basin Characterization Model – A monthly regional water balance software package (BCMv8) data release and model archive for hydrologic California (ver. 3.0, June 2023). Data release. Available from <https://www.usgs.gov/data/basin-characterization-model-a-monthly-regional-water-balance-software-package-bcmv8-data> (accessed August 11, 2023).
- Fontaine JB, Donato DC, Robinson WD, Law BE, Kauffman JB. 2009. Bird communities following high-severity fire: response to single and repeat fires in a mixed-evergreen forest, Oregon, USA. *Forest Ecology and Management* **257**:1496–1504.

- Forrestel AB, Ramage BS, Moody T, Moritz MA, Stephens SL. 2015. Disease, fuels and potential fire behavior: impacts of Sudden Oak Death in two coastal California forest types. *Forest Ecology and Management* **348**:23–30.
- Franklin JF et al. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. *Forest Ecology and Management* **155**:399–423.
- Franklin JF, Johnson KN. 2012. A restoration framework for federal forests in the Pacific Northwest. *Journal of Forestry* **110**:429–439.
- Frey SJK, Hadley AS, Johnson SL, Schulze M, Jones JA, Betts MG. 2016. Spatial models reveal the microclimatic buffering capacity of old-growth forests. *Science Advances* **2**:e1501392.
- Gaydos DA, Pacifici K, Rizzo DM, Meentemeyer RK. 2017. Resilience of diversity-disease risk interactions following wildfire disturbance. Page 7 in Frankel SJ, Harrell KM, editors. *Proceedings of the sudden oak death sixth science symposium*. Gen. Tech. Rep. GTR-PSW-255. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
- Gergel DR, Nijssen B, Abatzoglou JT, Lettenmaier DP, Stumbaugh MR. 2017. Effects of climate change on snowpack and fire potential in the western USA. *Climatic Change* **141**:287–299.
- Haas SE, Hall Cushman J, Dillon WW, Rank NE, Rizzo DM, Meentemeyer RK. 2016. Effects of individual, community, and landscape drivers on the dynamics of a wildland forest epidemic. *Ecology* **97**:649–660.
- Hammett EJ, Ritchie MW, Berrill J-P. 2017. Resilience of California black oak experiencing frequent fire: regeneration following two large wildfires 12 years apart. *Fire Ecology* **13**:91–103.
- Hart SJ, Schoennagel T, Veblen TT, Chapman TB. 2015. Area burned in the western United States is unaffected by recent mountain pine beetle outbreaks. *Proceedings of the National Academy of Sciences* **112**:4375–4380.
- Harvey BJ, Donato DC, Romme WH, Turner MG. 2013. Influence of recent bark beetle outbreak on fire severity and postfire tree regeneration in montane Douglas-fir forests. *Ecology* **94**:2475–2486.
- Hessburg PF et al. 2016. Tamm Review: management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. *Forest Ecology and Management* **366**:221–250.
- Hicke JA, Johnson MC, Hayes JL, Preisler HK. 2012. Effects of bark beetle-caused tree mortality on wildfire. *Forest Ecology and Management* **271**:81–90.
- Hicke JA, Meddens AJH, Kolden CA. 2016. Recent tree mortality in the western United States from bark beetles and forest fires. *Forest Science* **62**:141–153.
- Hunter JC. 1997. Fourteen years of change in two old-growth *Pseudotsuga-Lithocarpus* forests in northern California. *The Journal of the Torrey Botanical Society* **124**:273–279.
- Hunter JC, Parker VT. 1993. The disturbance regime of an old-growth forest in coastal California. *Journal of Vegetation Science* **4**:19–24.
- Jewell S, Vilsack TJ. 2014. *The National Strategy: the final phase in the development of the National Cohesive Wildland Fire Management Strategy*. U.S. Departments of the Interior and Agriculture, Washington, D.C.
- Klein A, Keeler-Wolf T, Evans JM. 2015. *Classification of the vegetation alliances and associations of Sonoma County, California: Volume 1 of 2 – Introduction, methods, and results*. California Department of Fish and Wildlife, Vegetation Classification and Mapping Program, and California Native Plant Society, Vegetation Program, Sacramento, CA.

- Kliejunas JT. 2011. A risk assessment of climate change and the impact of forest diseases on forest ecosystems in the western United States and Canada. Gen. Tech. Rep. PSW-GTR-236. U.S. Department of Agriculture, Forest Service, Pacific Southwest Station, Albany, CA.
- Kolb TE, Fettig CJ, Ayres MP, Bentz BJ, Hicke JA, Mathiasen R, Stewart JE, Weed AS. 2016. Observed and anticipated impacts of drought on forest insects and diseases in the United States. *Forest Ecology and Management* **380**:321–334.
- Lenihan JM, Bachelet D, Neilson RP, Drapek R. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. *Climatic Change* **87**:215–230.
- Lorimer CG, Porter DJ, Madej MA, Stuart JD, Veirs SD, Norman SP, O’Hara KL, Libby WJ. 2009. Presettlement and modern disturbance regimes in coast redwood forests: Implications for the conservation of old-growth stands. *Forest Ecology and Management* **258**:1038–1054.
- Lutz JA, van Wagendonk JW, Franklin JF. 2010. Climatic water deficit, tree species ranges, and climate change in Yosemite National Park. *Journal of Biogeography* **37**:936–950.
- Mandle L, Bufford JL, Schmidt IB, Daehler CC. 2011. Woody exotic plant invasions and fire: Reciprocal impacts and consequences for native ecosystems. *Biological Invasions* **13**:1815–1827.
- McDowell NG, Allen CD. 2015. Darcy’s law predicts widespread forest mortality under climate warming. *Nature Climate Change* **5**:669–672.
- McIntyre PJ, Thorne JH, Dolanc CR, Flint AL, Flint LE, Kelly M, Ackerly DD. 2015. Twentieth-century shifts in forest structure in California: Denser forests, smaller trees, and increased dominance of oaks. *Proceedings of the National Academy of Sciences* **112**:1458–1463.
- McNamara BA, Kane JM, Greene DF. 2019. Post-fire fuel succession in a rare California, USA, closed-cone conifer. *Fire Ecology* **15**:39.
- McPherson BA, Mori SR, Wood DL, Kelly M, Storer AJ, Svihra P, Standiford RB. 2010. Responses of oaks and tanoaks to the sudden oak death pathogen after 8y of monitoring in two coastal California forests. *Forest Ecology and Management* **259**:2248–2255.
- Meentemeyer RK, Cunniffe NJ, Cook AR, Filipe JAN, Hunter RD, Rizzo DM, Gilligan CA. 2011. Epidemiological modeling of invasion in heterogeneous landscapes: Spread of sudden oak death in California (1990–2030). *Ecosphere* **2**:1–24.
- Meentemeyer RK, Rank NE, Anacker BL, Rizzo DM, Cushman JH. 2008. Influence of land-cover change on the spread of an invasive forest pathogen. *Ecological Applications* **18**:159–171.
- Meentemeyer RK, Rizzo D, Mark W, Lotz E. 2004. Mapping the risk of establishment and spread of sudden oak death in California. *Forest Ecology and Management* **200**:195–214.
- Meigs GW, Campbell JL, Zald HSJ, Bailey JD, Shaw DC, Kennedy RE. 2015. Does wildfire likelihood increase following insect outbreaks in conifer forests? *Ecosphere* **6**:1–24.
- Merriam KE, Rentz E. 2010. Restoring fire to endemic cypress populations in northern California. Final report to the Joint Fire Science Program. JFSP Project No. 06-2-1-17. Available from <https://www.frames.gov/catalog/24925> (accessed October 7, 2019).
- Metlen KL et al. 2017. Rogue Basin cohesive forest restoration strategy: A collaborative vision for resilient landscapes and fire adapted communities. The Nature Conservancy, Portland, OR.
- Metz MR, Frangioso KM, Meentemeyer RK, Rizzo DM. 2011. Interacting disturbances: Wildfire severity affected by stage of forest disease invasion. *Ecological Applications* **21**:313–320.

- Metz MR, Frangioso KM, Wickland AC, Meentemeyer RK, Rizzo DM. 2012. An emergent disease causes directional changes in forest species composition in coastal California. *Ecosphere* **3**:1–23.
- Metz MR, Varner JM, Simler AB, Frangioso KM, Rizzo DM. 2017. Implications of sudden oak death for wildland fire management. *Forest Phytophthoras* **7**:30–44.
- Millar CI, Stephenson NL. 2015. Temperate forest health in an era of emerging megadisturbance. *Science* **349**:823–826.
- Nemens DG, Varner JM, Kidd KR, Wing B. 2018. Do repeated wildfires promote restoration of oak woodlands in mixed-conifer landscapes? *Forest Ecology and Management* **427**:143–151.
- North M, Collins B, Safford H, Stephenson NL. 2016. Montane forests. Pages 553–577 in Mooney H, Zavaleta E, editors. *Ecosystems of California*. University of California Press, Oakland, CA.
- Odion DC et al. 2014. Examining historical and current mixed-severity fire regimes in ponderosa pine and mixed-conifer forests of western North America. *PLoS ONE* **9**:e87852.
- Olimpi EM, Pasari JR, Skikne SA, Quadri Barba P, Ennis KK. 2016. Biological invasions. Pages 229–249 in Mooney H, Zavaleta E, editors. *Ecosystems of California*. University of California Press, Oakland, CA.
- Olson D, DellaSala DA, Noss RF, Strittholt JR, Kass J, Koopman ME, Allnutt TF. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou ecoregion. *Natural Areas Journal* **32**:65–74.
- Pausas JG. 2015. Bark thickness and fire regime. *Functional Ecology* **29**:315–327.
- Raffa KF, Aukema BH, Bentz BJ, Carroll AL, Hicke JA, Turner MG, Romme WH. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of bark beetle eruptions. *BioScience* **58**:501–517.
- Reeves SL. 2007. *Arbutus menziesii*. In: Fire Effects Information System [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available from <https://www.fs.usda.gov/database/feis/plants/tree/arbmen/all.html>.
- Reilly MJ, Monleon VJ, Jules ES, Butz RJ. 2019. Range-wide population structure and dynamics of a serotinous conifer, knobcone pine (*Pinus attenuata* L.), under an anthropogenically-altered disturbance regime. *Forest Ecology and Management* **441**:182–191.
- Restaino CM, Peterson DL, Littell J. 2016. Increased water deficit decreases Douglas fir growth throughout western US forests. *Proceedings of the National Academy of Sciences* **113**:9557–9562.
- Rizzo DM, Garbelotto M. 2003. Sudden oak death: Endangering California and Oregon forest ecosystems. *Frontiers in Ecology and the Environment* **1**:197–204.
- Sawyer JO. 2007. Forests of northwestern California. Pages 253–295 in Barbour M, Keeler-Wolf T, Schoenherr AA, editors. *Terrestrial vegetation of California*, 3rd edition. University of California Press, Berkeley, CA.
- Schierenbeck KA. 2017. Population-level genetic variation and climate change in a biodiversity hotspot. *Annals of Botany* **119**:215–228.
- Schmitt A, Trouvé R, Seynave I, Lebourgeois F. 2020. Decreasing stand density favors resistance, resilience, and recovery of *Quercus petraea* trees to a severe drought, particularly on dry sites. *Annals of Forest Science* **77**:52.
- Schroeder MJ, Glovinsky M, Henricks VF, Hood FC, Hull MK. 1964. Synoptic weather types associated with critical fire weather. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

- Serra-Diaz JM, Maxwell C, Lucash MS, Scheller RM, Laflower DM, Miller AD, Tepley AJ, Epstein HE, Anderson-Teixeira KJ, Thompson JR. 2018. Disequilibrium of fire-prone forests sets the stage for a rapid decline in conifer dominance during the 21st century. *Scientific Reports* **8**:6749.
- Sharples JJ. 2009. An overview of mountain meteorological effects relevant to fire behaviour and bushfire risk. *International Journal of Wildland Fire* **18**:737–754.
- Spies TA, Hemstrom MA, Youngblood A, Hummel S. 2006. Conserving old-growth forest diversity in disturbance-prone landscapes. *Conservation Biology* **20**:351–362.
- Spies TA, Hessburg PF, Skinner CN, Puettmann KJ, Reilly MJ, Davis RJ, Kertis JA, Long JW, Shaw DC. 2018. Chapter 3: Old growth, disturbance, forest succession, and management in the area of the Northwest Forest Plan. Pages 95–243 in Spies TA, Stine PA, Gravenmier R, Long JW, Reilly MJ, editors. *Synthesis of science to inform land management within the Northwest Forest Plan area*. Gen. Tech. Rep. PNW-GTR-966. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Steel ZL, Safford HD, Viers JH. 2015. The fire frequency-severity relationship and the legacy of fire suppression in California forests. *Ecosphere* **6**:8.
- Stephens SL, Collins BM, Fettig CJ, Finney MA, Hoffman CM, Knapp EE, North MP, Safford H, Wayman RB. 2018. Drought, tree mortality, and wildfire in forests adapted to frequent fire. *BioScience* **68**:77–88.
- Stephens SL, Fry DL. 2005. Fire history in coast redwood stands in the northeastern Santa Cruz Mountains, California. *Fire Ecology* **1**:2–19.
- Stephenson N. 1998. Actual evapotranspiration and deficit: Biologically meaningful correlates of vegetation distribution across spatial scales. *Journal of Biogeography* **25**:855–870.
- Stuart JD, Stephens SL. 2006. North Coast bioregion. Pages 147–169 in Sugihara NG, van Wagtenonk JW, Fites-Kaufmann J, Shaffer KE, Thode AE, editors. *Fire in California's ecosystems*. University of California Press, Berkeley, CA.
- Sturrock RN, Frankel SJ, Brown AV, Hennon PE, Kliejunas JT, Lewis KJ, Worrall JJ, Woods AJ. 2011. Climate change and forest diseases. *Plant Pathology* **60**:133–149.
- Syphard A, Rustigian-Romsos H. 2024. Modeling the potential impact of climate change on the distributions of six priority plants within the Golden Gate Biosphere Network. Conservation Biology Institute, Corvallis, OR.
- Syphard AD, Keeley JE. 2015. Location, timing, and extent of wildfire varies by cause of ignition. *International Journal of Wildland Fire* **24**:37–47.
- Tepley AJ, Thompson JR, Epstein HE, Anderson-Teixeira KJ. 2017. Vulnerability to forest loss through altered postfire recovery dynamics in a warming climate in the Klamath Mountains. *Global Change Biology* **23**:4117–4132.
- Thorne JH, Boynton RM, Flint LE, Flint AL. 2015. The magnitude and spatial patterns of historical and future hydrologic change in California's watersheds. *Ecosphere* **6**:1–30.
- Trombulak SC, Frissell CA. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology* **14**:18–30.
- Tukman Geospatial, Aerial Information Systems, Kass Green & Associates. 2018. 2018 Marin Countywide Fine Scale Vegetation Map. Prepared for the Golden Gate National Parks Conservancy. Tamalpais Lands Collaborative (One Tam), San Francisco, CA. Available from <https://tukmangeospatial.egnyte.com/dl/lh8BPnoMUK> (accessed November 10, 2023).

- USDA Forest Service. 2018. Somes Bar Integrated Fire Management Project: Final Environmental Assessment. U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, Six Rivers National Forest, Eureka, CA.
- van Mantgem PJ, Nensmith JCB, Keifer M, Knapp EE, Flint A, Flint L. 2013. Climatic stress increases forest fire severity across the western United States. *Ecology Letters* **16**:1151–1156.
- van Mantgem PJ van et al. 2009. Widespread increase of tree mortality rates in the western United States. *Science* **323**:521–524.
- Varner JM, Kuljian HG, Kreye JK. 2017. Fires without tanoak: The effects of a non-native disease on future community flammability. *Biological Invasions* **19**:2307–2317.
- Venette RC. 2009. Implication of global climate change on the distribution and activity of *Phytophthora ramorum*. Pages 58–59 in McManus KA, Gottschalk KW, editors. Proceedings of the 20th U.S. Department of Agriculture Interagency Research Forum on Invasive Species; 2009 January 13-16; Annapolis, MD. Gen. Tech. Rep. NRS-P-51. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA.
- Venette RC, Cohen SD. 2006. Potential climatic suitability for establishment of *Phytophthora ramorum* within the contiguous United States. *Forest Ecology and Management* **231**:18–26.
- Weed AS, Ayres MP, Hicke JA. 2013. Consequences of climate change for biotic disturbances in North American forests. *Ecological Monographs* **83**:441–470.
- Welch KR, Safford HD, Young TP. 2016. Predicting conifer establishment post wildfire in mixed conifer forests of the North American Mediterranean-climate zone. *Ecosphere* **7**:e01609.
- Williams AP, Abatzoglou JT, Gershunov A, Guzman-Morales J, Bishop DA, Balch JK, Lettenmaier DP. 2019. Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future* **7**:892–910.
- Young DJN, Stevens JT, Earles JM, Moore J, Ellis A, Jirka AL, Latimer AM. 2017. Long-term climate and competition explain forest mortality patterns under extreme drought. *Ecology Letters* **20**:78–86.
- Zald HSJ, Dunn CJ. 2018. Severe fire weather and intensive forest management increase fire severity in a multi-ownership landscape. *Ecological Applications* **28**:1068–1080.