Open Oak Woodlands and Savannas

Climate Change Vulnerability Assessment for the Golden Gate Biosphere Region

This document represents an evaluation of climate change vulnerability for open oak woodlands and savannas 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

Open oak woodland and savanna ecosystems in the Golden Gate Biosphere (GGB) region are comprised of a range of vegetative assemblages dominated by evergreen and deciduous oaks, including coast live oak (*Quercus agrifolia*), interior live oak (*Q. wislizeni*), blue oak (*Q. douglasii*), Oregon white oak (*Q. garryana*), and valley oak (*Q. lobata*; primarily occurs on moist sites north of San Francisco Bay; Davis et al. 2016b; Vuln. Assessment Worksheets, pers. comm., 2022). California black oak (*Q. kellogii*) can also occur at woodland edges in the GGB region, although it is relatively uncommon (McDonald 1990; Vuln. Assessment Worksheets, pers. comm., 2022). Within oak woodlands, oaks may be co-dominant with Pacific madrone (*Arbutus menzesii*), tanoak (*Notholithocarpus densiflorus*), or California bay (*Umbellularia californica*; Davis & Borchert 2006; Vuln. Assessment Worksheets, pers. comm., 2022). Oak ecosystem distribution and species composition are strongly influenced by site-specific factors including slope, elevation, drainage, and soil type (Altman & Stephens 2012; Davis et al. 2016b). Woodland structure tends to be relatively open (25–50% cover) with an understory often dominated by forbs, grasses, and a limited variety of scattered shrubs (Altman & Stephens 2012). By comparison, oak savannas are characterized by very low (<25%) canopy cover (Altman & Stephens 2012).

Fine-scale vegetation maps for San Mateo, Marin, and Sonoma Counties were used to identify seven vegetation classes that generally represent oak woodland and savanna communities within the GGB region (Tukman Geospatial et al. 2018), which occupy a combined total of 206,211 acres (Figure 1, Table 1). Of that, 16% (33,049 acres) is protected, with the largest area of protected lands managed by the California Department of Parks and Recreation (6,175 acres; Table 2).

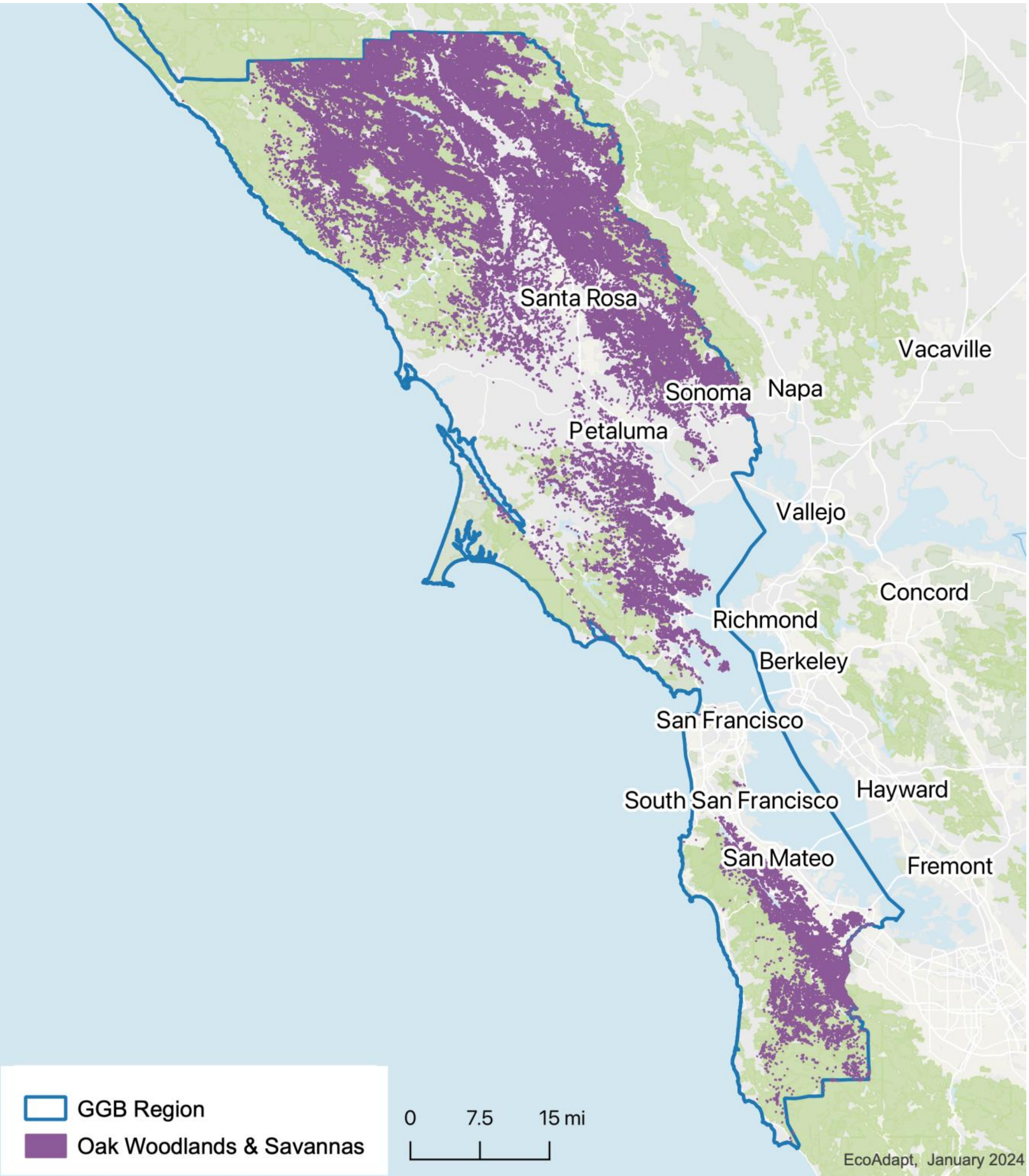

Figure 1. Distribution of vegetation map classes that likely represent oak woodland and savanna communities within the GGB region, derived from fine scale vegetation maps for San Mateo, Marin, and Sonoma Counties (Tukman Geospatial et al. 2018).

Table 1. Vegetation map classes likely to represent oak woodland and savanna communities within the GGB region, derived from fine scale vegetation maps for San Mateo, Marin, and Sonoma Counties (Tukman Geospatial et al. 2018).

Vegetation Map Class
Quercus (*agrifolia*, *douglasii*, *garryana*, *kelloggii*, *lobata*, *wislizeni*) Alliance
Quercus agrifolia Alliance
Quercus douglasii Alliance
Quercus garryana Alliance
Quercus kelloggii Alliance
Quercus lobata Mapping Unit
Quercus wislizeni – Quercus parvula (tree) Alliance

Table 2. 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
California Department of Parks and Recreation	6,175
Other protected lands	5,394
United States Army Corps of Engineers	4,665
San Francisco – Public Utilities Commission	3,353
Marin County Parks	3,151
Midpeninsula Regional Open Space District	2,454
Sonoma County Regional Parks Department	1,902
The Conservation Fund – California	1,248
Marin Municipal Water District	1,008
Audubon Canyon Ranch	861
San Mateo County Parks and Recreation Department	809
Sonoma County Agricultural Preservation and Open Space District	611
Sonoma Land Trust	421
National Park Service – Golden Gate National Recreation Area	371
National Park Service – Point Reyes National Seashore	254
United States Bureau of Land Management	170
California Department of Fish and Wildlife	93
California State Lands Commission	70
Peninsula Open Space Trust	42
TOTAL	**33,049**

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

Oak woodlands are sensitive to climate stressors that alter water availability and temperature, including changes in the amount and timing of precipitation, reduced soil moisture, increased drought, and warmer winter temperatures. Climate-driven changes in disturbance regimes (e.g., wildfire, disease, insect outbreaks) also have the potential to decrease oak health and increase mortality, and may alter woodland structure due to age- or species-specific patterns of mortality. Non-climate stressors, including development, agriculture, livestock grazing, invasive species, and fire exclusion, can exacerbate sensitivity of oak woodlands by contributing to habitat fragmentation, genetic isolation, reduced species and structural diversity, and climate-driven changes in fire regimes.

Although oak woodlands remain widely distributed throughout parts of the GBBN region, the historical extent of these ecosystems has been significantly reduced by development and other anthropogenic land uses, and many remaining woodlands are fragmented and/or degraded. Mature oaks are well-adapted to survive disturbances such as drought and wildfire, but increased mortality and reduced recruitment rates in more sensitive younger plant stages may limit the ability of oak woodlands to recover from future disturbances. Management strategies that are likely to increase the resilience of oak woodlands to climate impacts include the use of prescribed fire, targeted species removal, restoration of native perennial grasses and forbs, removal of invasive grasses and shrubs, climate-informed grazing management, and protection of oak woodlands in areas projected to remain climatically suitable and/or provide hydrologic refugia.

Sensitivity and Exposure → Moderate *(moderate 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 oak species by Ackerly et al. (2015) found that most are expected to experience declines, particularly under hotter scenarios and in the southern portions of the GGB region (Figure 2). The exception is coast live oak, which may expand under drier scenarios. Species distribution modeling conducted by the Conservation Biology Institute found similar results, with areas with climatic conditions suitable for coast live oak expected to increase by 14–19% under warm/moderate rainfall and hot/low rainfall scenarios, primarily in central coastal portions of the GGB region (Figure 3; Syphard & Rustigian-Romsos 2024). However, under a warm/high rainfall scenario climatically-suitable areas are projected to decline by 13%, with the declines concentrated in inland areas north of San Francisco Bay. Syphard and Rustigian-Romsos (2024) also modeled climatic suitability for black oak, finding that suitable habitat for the species is projected to contract by 25–96% compared to the current area (Figure 4). These changes are most closely associated with projected increases in summer maximum and winter minimum temperatures. Across the three climate scenarios used in this study, the existing areas of suitable habitat for black oak in the northern portion of the GGB region would decline in both size and degree of suitability, leaving some small patches of suitable habitat surrounded by large areas of contraction to the west and northwest of Austin Creek State Recreation Area.

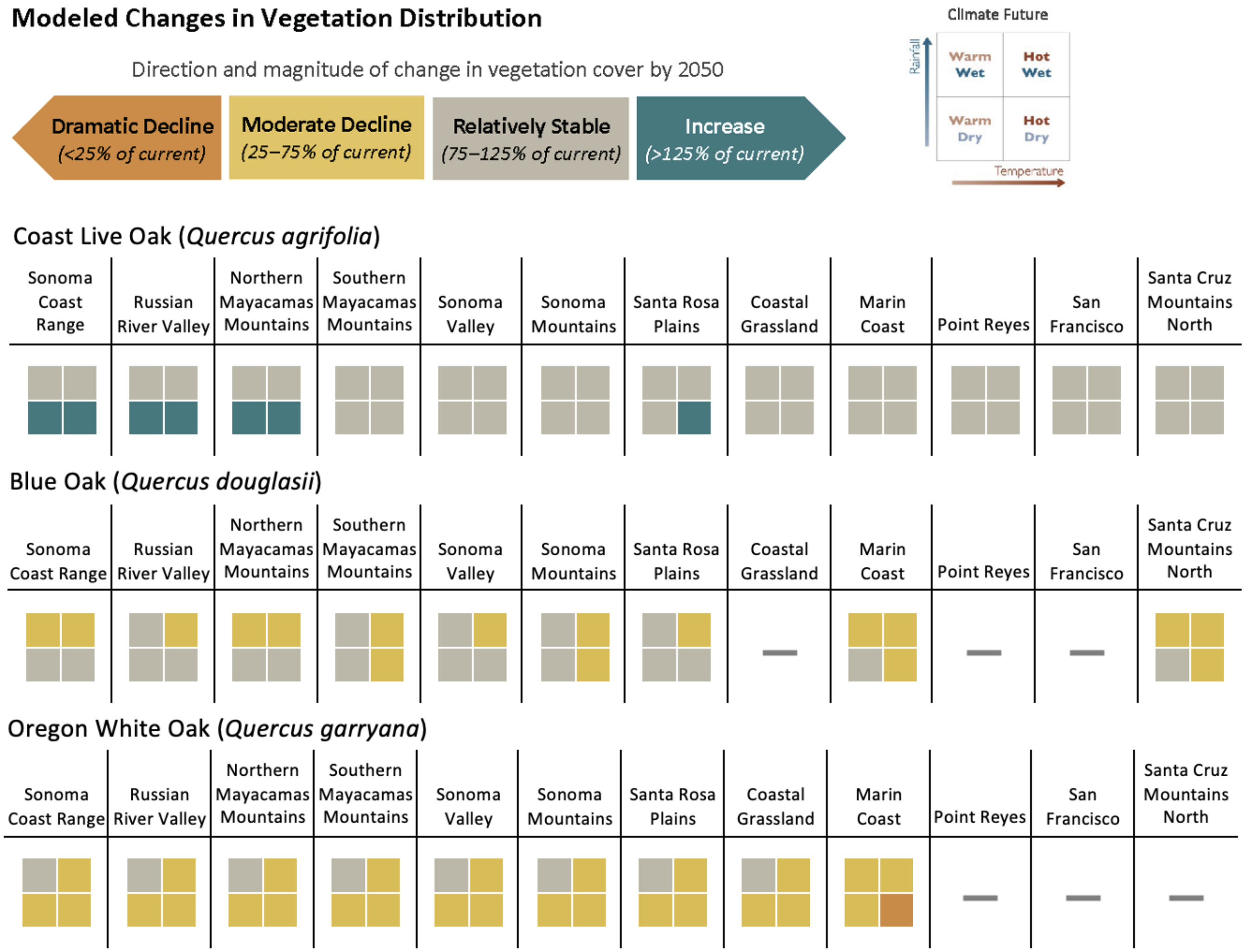

Figure 2. Projected trends in vegetation distribution by mid-century (~2050) within landscape units overlapping the GGB region, based on results from Ackerly et al. (2015). The four squares refer to a range of possible climate futures that vary with respect to temperature and precipitation, with the 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).

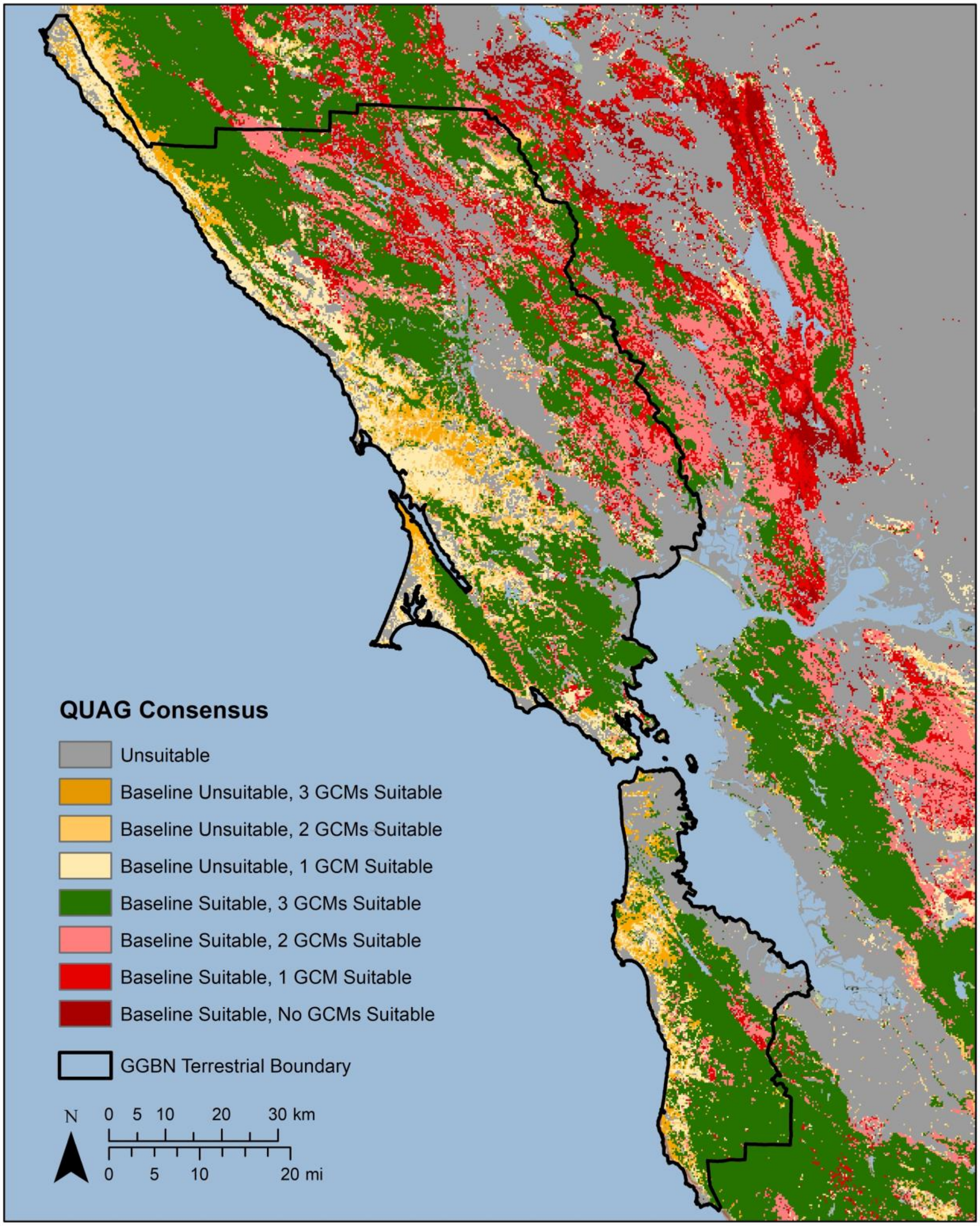

Figure 3. Future climatic suitability for coast live oak (QUAG) for an end-of-century time frame (2070–2099 compared to 1981–2010). Species distribution model compares baseline (current distribution) to three global climate models (GCMs) under the RCP 8.5 emissions scenario. GCMs included are CNRM-CM5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

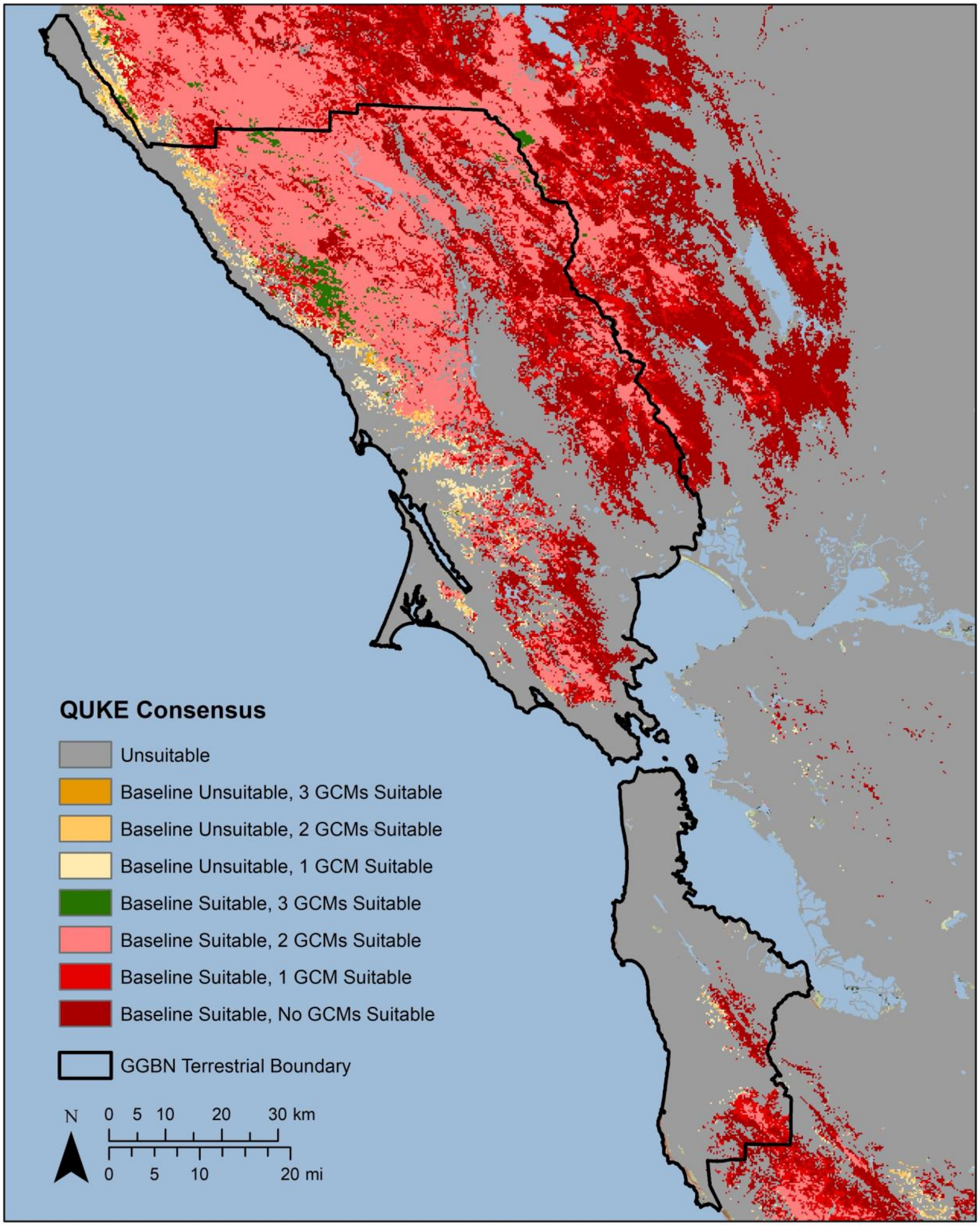

Figure 4. Future climatic suitability for California black oak (QUKE) for an end-of-century time frame (2070–2099 compared to 1981–2010). Species distribution model compares baseline (current distribution) to three global climate models (GCMs) under the RCP 8.5 emissions scenario. GCMs included are CNRM-CM5 (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 → Moderate *(moderate confidence)*

- **Changes in precipitation and soil moisture** may impact oak regeneration and ultimately species composition by reducing acorn production, seedling establishment, and tree growth (Trowbridge et al. 2005; Tyler et al. 2006; Davis et al. 2016a). Oak savannas and woodlands experience high year-to-year variability in rainfall, which contributes to variable acorn production and seedling recruitment (Koenig et al. 1996; Stahle et al. 2013). Climate change is projected to further increase interannual precipitation variability and drive shifts in seasonal rainfall patterns that are likely to contribute to more intense periods of flooding and longer dry periods (Luković et al. 2021). Increases in winter rainfall and flooding are likely to create saturated soil conditions that are not well tolerated by some oak species, such as black oak (McDonald 1990), and may drive higher oak mortality on more marginal or shallower soils (Harris et al. 1980). Wetter winter conditions may also enhance spore production and transmission of *Phyophthora ramorum* (the pathogen which causes sudden oak death), to which coast live oak and California black oak are susceptible (Davidson et al. 2003; Cunniffe et al. 2016; Cobb et al. 2020).

  In general, oak seedlings and saplings are more sensitive to water stress than adults, in part because their root systems are not able to reach the groundwater sources utilized by mature oaks, and they are more likely to experience competition for near-surface soil moisture from vegetation such as invasive annual grasses (Mahall et al. 2009; McLaughlin & Zavaleta 2012; Davis et al. 2016a; Gedalof et al. 2022). As a result of this age-dependent sensitivity to moisture stress, range contractions may occur where seedlings are unable to survive in areas that would otherwise be considered suitable for persistence of mature trees (McLaughlin & Zavaleta 2012; McLaughlin et al. 2017). Shifts in species composition, including potential shifts in dominance from one oak species to another, may occur as altered patterns of moisture stress drive changes in oak abundance and distribution. For example, modeling suggests that oak woodland composition within the GGB region may shift, with oaks adapted to warmer, drier conditions replacing those that are less tolerant of drought and likely leading to an overall loss of species diversity (Ackerly et al. 2020).

- **Increases in the frequency and/or severity of drought** are likely to decrease recruitment and growth and increase mortality rates in oaks, especially where competition with annual plants further reduces available moisture for oak seedlings (Gordon & Rice 1993; Mahall et al. 2009; Gedalof et al. 2022). Persistence of hydrologic refugia such as shaded areas with accessible groundwater may allow oaks to resist increasing drought stress (McLaughlin et al. 2017). However, greater drought sensitivity in seedlings and saplings could constrain successful regeneration of mature oak woodlands (McLaughlin & Zavaleta 2012). Species that tend to be found in association with wetter climate conditions, such as black oak, may be particularly susceptible to drought (McDonald 1990; Davis et al. 2016a) and may ultimately be extirpated from areas where their distribution is already very limited (e.g., the Peninsula watershed; S. Simono, pers. comm., 2023).

- **Increasing air temperature** and corresponding **increases in winter soil temperatures** are likely to reduce successful recruitment of oak species that benefit from or require a period of cold temperatures to break seed dormancy and initiate germination, including coast live oak, black oak, and interior live oak (McCreary 2009). However, in general the upper limits of temperature tolerance by seedling and adult oaks is not well understood (Davis et al. 2016a; Vuln. Assessment Worksheets, pers. comm., 2022).

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

- Oaks are well-adapted to low- and moderate-intensity fires, which enhance acorn germination, reduce pest and pathogen loads, and maintain the open canopy structure characteristic of this woodland type by preventing establishment and eventual overtopping by conifers (Kauffman & Martin 1987; Cocking et al. 2012; Long et al. 2016). However, **climate-driven changes in the frequency and/or intensity of wildfires** may increase oak injury and mortality, particularly for seedlings and saplings that are more vulnerable to intense wildfires relative to mature trees (Swiecki & Bernhardt 2002; Holmes et al. 2008). As a result, increases in the frequency of high-severity fires may negatively impact oak woodland persistence where seedlings are unable to mature and produce acorns before the next fire (Holmes et al. 2008). Over time, these dynamics can lead to the conversion of oak-dominated systems to shrublands or grasslands (George & Alonso 2008). Fire suppression can exacerbate these impacts by allowing encroachment of shrubs and conifers into open woodlands where they outcompete oaks and increase fuel loading, contributing to more intense fires (Cocking et al. 2012; Stephens et al. 2023).

  Increased disease is likely to cause higher oak mortality as changes in temperature and precipitation regimes impact pathogen production and transmission (Kliejunas 2011; Kolb et al. 2016; Kozanitas et al. 2022) as well as tree defenses, host susceptibility, and host community interactions (Kliejunas 2010; Dillon & Meentemeyer 2019). California black oak and coast live oak are susceptible to sudden oak death caused by the introduced pathogen *P. ramorum*, along with tanoak (Rizzo et al. 2002; McPherson et al. 2010; Cobb et al. 2020). In addition to causing direct mortality, *P. ramorum* can also weaken oaks and facilitate increased vulnerability to insect attacks (McPherson et al. 2010). High rates of tree mortality and subsequent stump sprouting can also lead to increases in available fuels, potentially altering fire behavior (Forrestel et al. 2015; Metz et al. 2017).

- **Increases in insect pests** may contribute to declines in oak health and increases in mortality, particularly if warmer temperatures drive range expansions in insects such as the introduced goldspotted oak borer (GSOB; *Agrilus arrogutatus* and a closely related species *A. coxalis*), which have been documented to infect at least three *Quercus* species in San Diego County (Coleman & Seybold 2008; Coleman et al. 2011). Drought stress appears to contribute to GSOB-driven mortality, and GSOB damage to the tree can increase stress and vulnerability to secondary attack (Coleman & Seybold 2008). While its current distribution is in southern California, assessments of potential GSOB spread suggest that much of California will be climatically suitable for this insect by the end of the century (Venette et al. 2015). The Mediterranean oak borer (*Xyleborus monographus*) has recently been discovered in Napa, Sonoma, and Lake Counties, and trees may be more susceptible if they are already suffering from drought, or other pests or diseases (UCANR 2023).

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.

- **Residential and commercial development** and associated **roads, highways, and trails** have resulted in the loss and fragmentation of oak woodlands throughout the GGB region, particularly in the more urbanized San Francisco Bay Area (Davis et al. 2016b; Baumgarten et al. 2021). Impacts to oak woodlands from development include reduced genetic exchange and seedling recruitment in fragmented populations (Sork et al. 2002), reduced diversity of oaks and their wildlife and plant associates (Merenlender et al. 1998; Easterday et al. 2016), and shifts in dominance among oak species (Easterday et al. 2016). Development can also impact groundwater tables, leading to loss of water supply and increased stress on oak trees (McLaughlin et al. 2017). Development and associated human activity can also increase wildfire ignitions and is associated with fire suppression within developed areas and the wildland-urban interface, exacerbating climate-driven shifts in wildfire regimes (Davis & Borchert 2006; Mann et al. 2016).
- Significant loss of oaks has occurred as trees are removed for **livestock grazing** and **agriculture**, particularly row crops and orchards in the Bay Area (Davis et al. 2016b; Baumgarten et al. 2021). Historic and ongoing impacts of grazing on oaks include soil compaction, acorn and seedling destruction, and shifts in plant composition, but these impacts vary depending on grazing intensity and timing (Hall et al. 1992; Tyler et al. 2006; Davis et al. 2016b). Livestock grazing can in some cases have indirect positive effects on oak recruitment by reducing competing grasses (Tyler et al. 2006). However, grazing can also decrease oak seedling and sapling growth and survival (Davis et al. 2011), and livestock activity can compact soils, increase erosion, and damage understory shrubs that protect fallen acorns and seedlings from herbivory and desiccation (Davis et al. 2016b). Grazing has also been shown to slow post-fire recovery of oak woodlands (Callaway & Davis 1993; George & Alonso 2008).
- **Invasive and problematic species** impact the health and survival of oak woodlands. Invasive grasses alter species composition within oak woodland understories, displacing native annuals

and seedling bunchgrasses, and competing for the shallow moisture and light needed by oak seedlings (Gordon & Rice 1993; Holmes et al. 2011). Invasive annual grasses also increase the availability and continuity of fine fuels, contributing to changes in fire frequency and behavior (D'Antonio & Vitousek 1992; Chambers et al. 2019). Invasive broom species, particularly French broom (*Genista monspessulana*), can exclude native species and alter fuel loading (Bossard 2000). California bay, although native, can be considered problematic, as it plays a major role in disease transmission of sudden oak death (Kozanitas et al. 2022).

Although many wildlife species feed on oak acorns, high abundances of species lacking predator controls, such as deer (*Odocoileus hemionus*), can impact oaks through intensive browsing and acorn predation (Bowyer & Bleich 1980; Vuln. Assessment Worksheets, pers. comm., 2022). Introduced species such as feral pigs (*Sus scrofa*) and turkeys (*Meleagris gallopavo*) can also impact oaks through acorn predation and soil disturbance (Sweitzer & Vuren 2002; Fehring et al. 2007). Invasive pests such as the gold-spotted oak borer represent extant and emerging threats to a variety of oak species, particularly if they are already stressed by drought or other pathogens (Coleman et al. 2011; Venette et al. 2015).

- **Fire exclusion and suppression** has altered historic wildfire regimes in oak woodlands, increasing fire return intervals in the GGB region from every few years (prior to European settlement) to 20+ years, especially in areas where fire suppression to protect human property and lives is a management priority (Davis & Borchert 2006; Panorama Environmental 2019). Oak woodlands in the GGB region were managed by indigenous people using fire for thousands of years prior to European settlement (Anderson 2007; Long et al. 2016), and reduction in wildfire frequency in these fire-adapted communities has resulted in shifts in oak woodland species composition and ecosystem structure throughout the region (Davis & Borchert 2006; Anderson 2007). Specifically, encroachment of woody plants such as Douglas-fir (*Pseudotsuga menziesii*) into oak savannas and woodlands has resulted in increasing canopy closure and, in some cases, transition to conifer-dominated ecosystems (Davis & Borchert 2006; Cocking et al. 2012).

Adaptive Capacity → High *(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 → Moderate (high confidence)

Oak woodlands are broadly distributed throughout the GGB region, though some species have more restricted habitat associations. For example, black oak is generally associated with cooler microclimates (McDonald 1990) while coast live oak and blue oak tend to be more widespread (Stahle et al. 2013; McPherson et al. 2015). Oak woodlands have suffered historic and ongoing declines in extent and continuity as a result of agriculture, development (Davis et al. 2016a, 2016b; Easterday et al. 2016), and introduced disease (Rizzo et al. 2002). Increases in invasive annual grasses, mediated in many cases by fire exclusion and agricultural expansion, have further altered and degraded ecosystem structure and composition (Holmes et al. 2011; Davis et al. 2016b). Low recruitment is a recognized problem for multiple species, and has been linked to population declines in valley oak and blue oak (Tyler et al. 2006; Zavaleta et al. 2007).

Multiple dispersal mechanisms including acorn masting (i.e., the production of large seed volumes every few years) and resprouting may help buffer species against fragmentation and climatic change (Vuln. Assessment Worksheets, pers. comm., 2022). However, relatively short pollen and acorn dispersal distances can limit pollination and genetic exchange in oak populations, which could reduce shifts in oak species' ranges in response to climate change (Koenig & Ashley 2003). Hybridization does occur among oak species, and has the potential to increase genetic diversity and enhance tree tolerance for changing climate regimes, as well as buffer against fragmentation of species-specific groups (Ortego et al. 2014, 2017). However, rates of hybridization are complex and variable and can be rare, even for closely related sympatric species such as blue and valley oak in central California (Craft et al. 2002).

Ecosystem diversity → High (high confidence)

Oak woodlands can include a variety of oak species as well as a range of other hardwoods and conifers (Davis et al. 2016b). As dominant canopy species, oaks create favorable microclimates for understory vegetation and provide habitat for wildlife (Merenlender et al. 1998; Borchert & Tyler 2010; Davis et al. 2016b; Long et al. 2016), including insects, birds, mammals, reptiles and amphibians (Merenlender et al. 1998; Zack et al. 2005; Altman & Stephens 2012). Historically, plant species diversity within oak-dominated ecosystems was high, particularly in woodlands with a more open structure where herbaceous understories can be very diverse (Davis et al. 2016b; Long et al. 2016). However, both plant and wildlife diversity in oak woodlands has declined over the past century due to factors such as fire exclusion and invasive species (Holmes et al. 2011; Cocking et al. 2012; Stephens et al. 2020, 2023).

Resistance and recovery → Moderate (low confidence)

Mature oaks are generally resilient to disturbances such as drought and wildfire (Allen 2015; Hammett et al. 2017). They utilize multiple reproductive strategies including resprouting (McCreary 2009; Hammett et al. 2017) and mast seeding, which increases their persistence and opportunities for successful recruitment (Koenig et al. 1996). Several species, including blue oak, coast live oak, and valley oak, also have deep root systems that can access groundwater during periods of drought (Miller et al. 2010; Allen 2015). Seedlings and saplings are more vulnerable to disturbances, so declines in recruitment resulting from both climate and non-climate stressors (e.g., grazing, competition from invasive grasses, drought, flooding) may limit oak regeneration (Hall et al. 1992; Trowbridge et al. 2005; Mahall et al. 2009; Gedalof et al. 2022). Coast live oak and California black oak are additionally vulnerable to mortality from sudden oak death, and this threat may increase under climate change requiring more active management to facilitate resistance and recovery (Cunniffe et al. 2016).

Management potential → High (moderate confidence)

Oak woodlands are iconic landscapes in California, and are highly valued by the public for their beauty, recreational opportunities, and wildlife habitat (Standiford & Huntsinger 2012; Davis et al. 2016b; Vuln. Assessment Worksheets, pers. comm., 2022). Oak woodlands are habitat for several important game species and are frequently used for livestock grazing (Bowyer & Bleich 1980; Mensing 2006; Huntsinger et al. 2010; Davis et al. 2016b). They are also of great cultural significance to California tribes, who use cultural burning and other practices to maintain abundant acorn crops and robust, open-canopy oak ecosystems (Mensing 2006; Anderson 2007; Long et al. 2016; Stephens et al. 2023). Societal support for oak woodlands is increasing as a result of enhanced, though unevenly practiced, regulatory protection, and out of growing concern for the impacts of sudden oak death (Light & Pedroni 2002; Cushman & Meentemeyer 2008). However, many of the areas of the region where oak woodlands remain are subject to high development pressure, and as such are at risk of conversion and degradation (Easterday et al. 2016; Vuln. Assessment Worksheets, pers. comm., 2022).

There is high potential for management strategies to support climate adaptation by creating favorable conditions for oak germination, growth, and reproduction (McCreary 2009; Hankins 2015). Ungulate and rodent exclusion can significantly reduce herbivory of acorns, seedlings, and saplings that contributes to low recruitment rates (Davis et al. 2011), and is particularly effective when paired with oak restoration planting (Swiecki & Bernhardt 1998; McCreary 2009). Restoring frequent, low intensity fire in these communities encourages oak recruitment, reduces competition from invasive species, and enhances native understory vegetation (Holmes et al. 2011; Hankins 2015; Long et al. 2016). Other management strategies that may support oak woodland adaptation to future climate changes including restoration of native understory grasses and forbs, climate-informed grazing management (i.e., altering intensity and timing of grazing in response to changing climate conditions), hunting to reduce populations of overabundant consumers such as feral pigs, and increased seed collection efforts (Sweitzer & Vuren 2002; McCreary 2009; Vuln. Assessment Worksheets, pers. comm., 2022). In coast live oak or black oak woodlands, targeted removal of California bay can reduce sporulation of *P. ramorum* and subsequent infection of reproductive-age oaks (Kozanitas et al. 2022). Protection efforts should focus on areas that are predicted to remain climatically suitable for dominant oak species, such as hydrologic refugia that buffer against water stress (Kueppers et al. 2005; McLaughlin & Zavaleta 2012; McLaughlin et al. 2017). Finally, modeling work and small-scale experimental translocations have been conducted to evaluate assisted migration of oaks in other parts of North America and Europe in order to facilitate adaptation of oak woodlands to shifting climate conditions (Iverson 2013; McCartan et al. 2015), and this may increasingly be considered in California. Common garden experiments of paired local and trailing edge blue oak seeds, termed ‘field gene banking’, supported that trailing edge seedlings showed lower survival but also lower levels of disease and herbivory, traits which are potentially adaptive for a drier future (McLaughlin et al. 2022).

Recommended Citation

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Further information on the Golden Gate Biosphere Region Climate Adaptation Project is available on the project page (www.ecoadapt.org/goto/GGBRClimateProject).

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