Coastal Redwood Forests

Climate Change Vulnerability Assessment for the Golden Gate Biosphere Region

This document represents an evaluation of climate change vulnerability for coastal redwood 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

Coastal redwood forests in the Golden Gate Biosphere (GGB) region are near the southern edge of their distribution, which is limited to the coastal fog zone and extends from central California into southern Oregon (Olson et al. 1990; Burns et al. 2018). Coast redwood (*Sequoia sempervirens*) is a very long-lived species, with some individuals living over 2,500 years. They can reach heights of over 115 m (377 ft), which makes them the tallest and largest trees on Earth (Sillett et al. 2015). Their great height and biomass allows them to influence climate conditions (e.g., light, temperature, humidity, soil moisture) within their immediate vicinity (Mooney & Dawson 2016).

Coastal redwood forests have a multi-layered canopy, with the upper layer comprised of coast redwood and lower layers typically comprised of shade-tolerant species such as tanoak (*Notholithocarpus densiflorus)*, California bay laurel (*Umbellularia californica*), and Douglas-fir (*Pseudotsuga menziesii*; Burns et al. 2016). Understory vegetation is dominated by species adapted to the cool, moist microclimate and low light levels found under redwood canopies (Olson et al. 1990; Mooney & Dawson 2016). Forest structure and composition in second- and third-growth stands varies depending on site conditions (e.g., elevation, soil type, topography), historical logging practices, and time since disturbance, but in general they are denser and skewed towards younger age classes (Olson et al. 1990; Mooney & Dawson 2016; Burns et al. 2018). Old-growth forest patches are present throughout the GGB region, but are less extensive than in northern areas (Olson et al. 1990; Lorimer et al. 2009; Mooney & Dawson 2016).

Fine-scale vegetation maps for San Mateo, Marin, and Sonoma Counties were used to identify the distribution of the *Sequoia sempervirens* vegetation alliance that represents coastal redwood forests within the GGB region (Tukman Geospatial et al. 2018), which occupies 162,677 acres (Figure 1). Of that, 30% (48,495 acres) is protected, with the largest area of protected lands managed by the California Department of Parks and Recreation (14,623 acres; Table 1).

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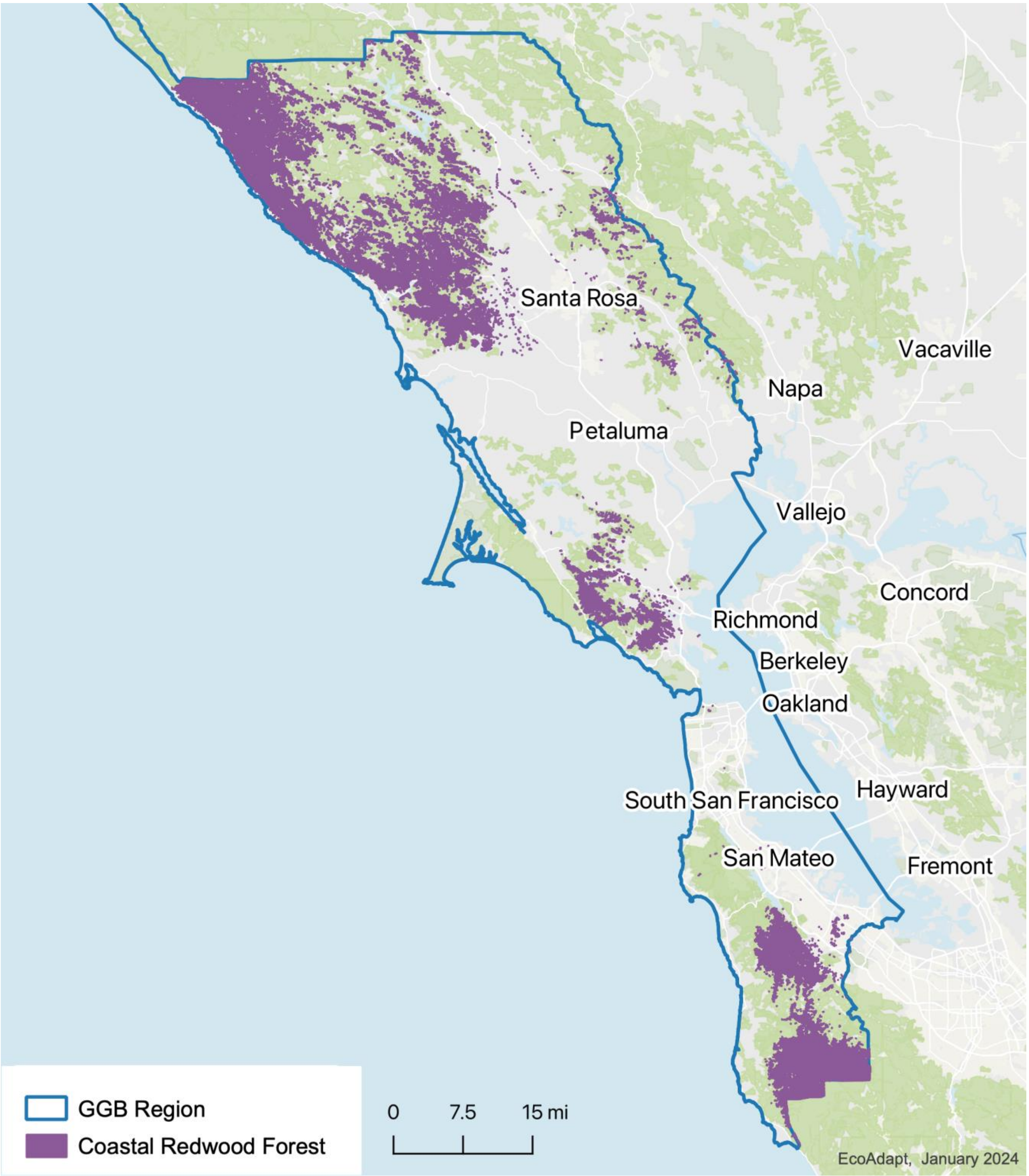

Figure 1. Distribution of the *Sequoia sempervirens* vegetation alliance that represents coastal redwood forests within the GGB region, derived from fine scale vegetation maps for San Mateo, Marin, and Sonoma Counties (Tukman Geospatial et al. 2018).

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
California Department of Parks and Recreation	14,623
San Mateo County Parks and Recreation Department	7,236
Midpeninsula Regional Open Space District	6,562
The Conservation Fund – California	6,061
Marin Municipal Water District	4,105
Sonoma County Agricultural Preservation and Open Space District	2,369
Other protected lands	2,178
National Park Service – Point Reyes National Seashore	1,418
National Park Service – Golden Gate National Recreation Area	1,211
Marin County Parks	850
San Francisco – Public Utilities Commission	685
Peninsula Open Space Trust	328
Audubon Canyon Ranch	259
United States Army Corps of Engineers	247
Sonoma County Regional Parks Department	227
United States Bureau of Land Management	75
Sonoma Land Trust	55
California Department of Fish and Wildlife	5
TOTAL	**48,495**

Ecosystem Vulnerability → High *(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

Coastal redwood forests are sensitive to changes in climatic factors that increase water stress, which affects redwood growth and recruitment as well as understory and mid-canopy species composition and structure. Whereas mature redwood trees are highly resistant to disturbances and their sprouting ability enables recovery following injury to trunks or limbs, climate-driven changes in disturbances such as wildfire and disease may drive shifts in species composition and forest structure within the sub-canopy and understory. Non-climate stressors further exacerbate the impacts of these changes; for instance, a history of logging followed by fire exclusion and suppression in second-growth forests has resulted in dense growth of small trees that increases moisture stress and vulnerability to large, intense wildfires.

The extent of old-growth coastal redwood forests has been significantly reduced by timber harvesting. Connectivity among remaining old-growth forest patches has declined, and the integrity and spatial complexity of second-growth forests has been degraded across the region that is also projected to become less climatically suitable for coast redwood over the coming decades. Because redwoods are long-lived, recover rapidly following injury, and are resistant to insects, disease, and fire, old-growth forests may respond more slowly to climate changes than many other forest types and therefore may serve as climate refugia for many wildlife species, at least in the near term. However, long-lived species such as redwoods are also slow to adapt, and degraded second- and third-growth forests may be less able to recover from disturbances, particularly on drier sites. Conservation of remaining old-growth forest areas is critical, but it is also important to protect biologically-significant second-growth forests that connect existing intact forest patches. In degraded second-growth forests, the scientific literature supports several management strategies (e.g., thinning, strategic crown manipulation) that may enhance or restore ecosystem functioning and increase tree growth rates and structural complexity, accelerating the development of old-growth forest characteristics and reducing vulnerability to climate impacts.

Sensitivity and Exposure → High *(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 coast redwood by Ackerly et al. (2015) found that this species is sensitive to increased water deficit and high temperatures in the GGB region, with moderate declines projected for most landscape units under a hot/dry climate scenario (Figure 2). Similarly, species distribution modeling conducted by the Conservation Biology Institute found areas within the GGB region where climatic conditions are expected to be suitable for coast redwood are projected to increase by 15% under the warm/moderate rainfall scenario, but contract by 9% to 14% under the warm/high rainfall and hot/low rainfall models (Figure 3; Syphard & Rustigian-Romsos 2024). These changes are most closely associated with changes in summer precipitation and winter minimum temperature. Across all models, the areas of potential contraction are most likely along the inland edge of the species distribution, while stable areas of climatically-suitable habitat are primarily maintained along the coast.

These results are in line with previous studies suggesting that conditions are likely to become increasingly unsuitable for coast redwood in future decades due to warmer temperatures, water stress, and possible changes in the timing and frequency of coastal fog, with the largest declines in the southern portion of their range (Flint & Flint 2012; Fernández et al. 2015; Thorne et al. 2016, 2017; DellaSala et al. 2018). This includes the GGB region, where coastal redwood forests are largely already limited to cooler, moister sites, which limits their options for expansion into previously unoccupied areas (Ackerly et al. 2020). Sites that may continue to offer refugia as conditions change over the coming decades including cool north-facing slopes, riparian and moist valleys, and areas of persistent fog where summer drought is reduced (Ackerly et al. 2015, 2020).

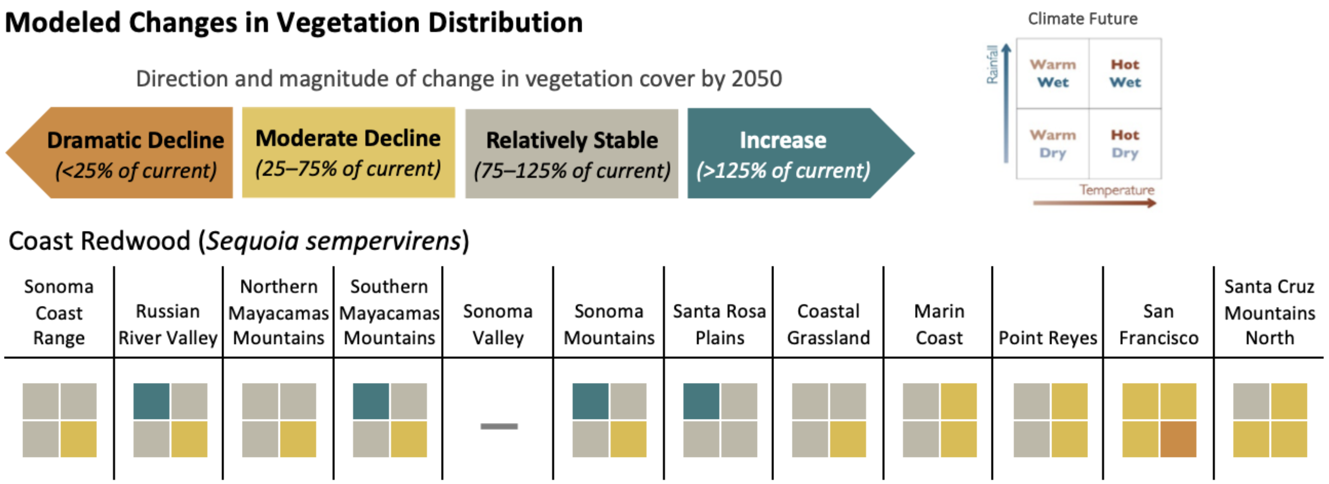

Figure 2. Projected trends in vegetation distribution by mid-century (~2050) within landscape units overlapping the GGB region, based on results from Ackerly et al. (2015). The four squares refer to a range of possible climate futures that vary with respect to temperature and precipitation, with the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

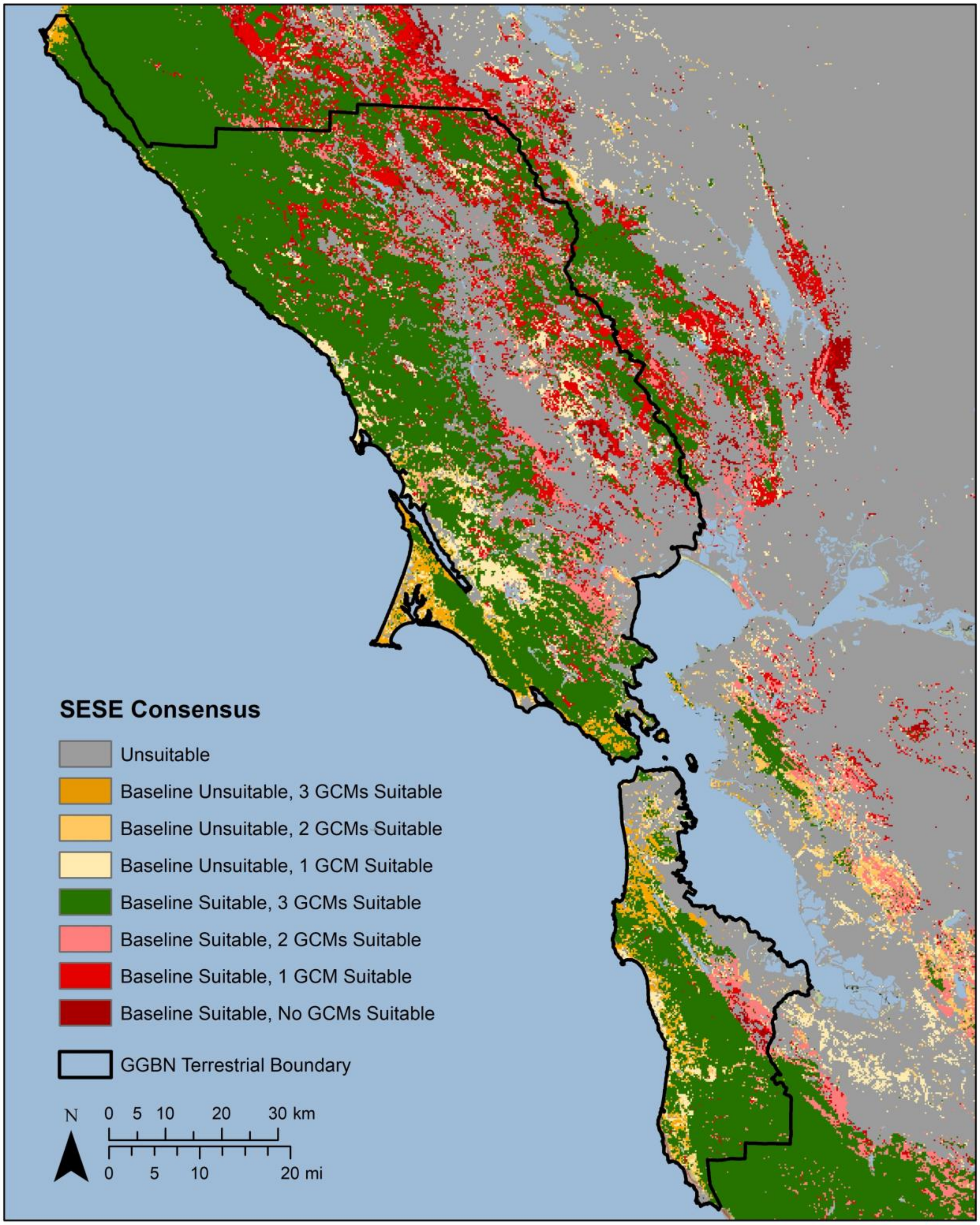

Figure 3. Future climatic suitability for coast redwood (SESE) for an end-of-century time frame (2070–2099 compared to 1981–2010). Species distribution model compares baseline (current distribution) to three global climate models (GCMs) under the RCP 8.5 emissions scenario. GCMs included are CNRM-CM5 (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 *(moderate confidence)*

- **Changes in precipitation patterns**, **reduced coastal fog**, and **increased drought** are likely to enhance moisture stress in coastal redwood forests (Dawson 1998; Burgess & Dawson 2004; Johnstone & Dawson 2010), decreasing redwood growth and seedling recruitment (Olson et al. 1990; Carroll et al. 2014) and potentially driving range contractions over time (Johnstone & Dawson 2010; Flint & Flint 2012; Ackerly et al. 2020). Coast redwood is a shallow-rooted species that requires high levels of soil moisture, and within the GGB region they are near the southern edge of their range where they experience higher moisture stress and lower growth and productivity compared to more northern sites (Olson et al. 1990; Carroll et al. 2014; Van Pelt et al. 2016; Sillett et al. 2022). Within this region, they are primarily found in riparian systems or on ridges where abundant fog relieves summer drought stress (Olson et al. 1990; Vuln. Assessment Worksheets, pers. comm., 2022). Redwoods do have some adaptations that help them cope with moderately dry conditions (Dagley et al. 2017; De La Torre et al. 2022), including shoot dimorphism (i.e., two functionally-distinct shoot morphotypes) that helps them to excel at rainy-season photosynthesis and dry-season water absorption (Chin et al. 2022). However, periods of more severe water stress can result in significant growth declines in redwood seedlings (Ambrose et al. 2015) and it is unknown whether the species will experience mortality and/or range shifts under drier future conditions (Burns et al. 2018). Increased water stress, including that resulting from potential reductions in coastal fog, may also alter understory species composition, plant density, and percent cover (Dawson 1998; Mahony & Stuart 2000; Santiago & Dawson 2014). Forests that have experienced historical timber harvest are more vulnerable to climate-driven changes in moisture regimes, as the removal of large redwoods alters the hydrological balance and forest microclimate, reducing the ability of the ecosystem to capture fog water and creating more xeric site conditions (Dawson 1998; Mooney & Dawson 2016).
- **Warmer air temperatures** are likely to increase evaporative demand within coastal redwood forests, enhancing water stress (Flint & Flint 2012). This is particularly true in the drier southern portion of their range, where redwood growth has been negatively correlated with high spring and summer maximum temperatures (Carroll et al. 2014, 2018; Sillett et al. 2022). Because water stress is the limiting factor for coastal redwood forests in the GGB region (Carroll et al. 2014, 2018), the possibility of benefits from a longer growing season is limited, and overall these patterns suggest possible growth reductions may occur under future climate conditions.
- **Altered stream flows**, including higher peak flows and increased flow variability and flashiness (Burke & Ficklin 2017; Swain et al. 2018), may increase erosion and sedimentation that could impact alluvial stands, as well as the structure and function of streams associated with redwood forests (Vuln. Assessment Worksheets, pers. comm., 2022).

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

- **Climate-driven changes in wildfire regimes**, including more frequent high-intensity fires, have the potential to significantly alter forest composition and structure (Stuart & Stephens 2006; Mahdizadeh & Russell 2021). Mature coast redwoods are highly resistant to fire due to thick bark that protects them from injury or mortality during all but the most intense fires (Lorimer et al. 2009; Ramage et al. 2010; Lazzeri-Aerts & Russell 2014; Mahdizadeh & Russell 2021), and redwoods, tanoak, and several other associated species also have the ability to resprout following topkill (Ramage et al. 2010; Simler et al. 2017). Historically, frequent low-intensity surface fires, primarily occurring as a result of cultural burning by California indigenous peoples, played an important role in maintaining overall ecosystem structure and function in coastal redwood forests (Huntsinger & McCaffrey 1995; Stephens & Fry 2005; Ramage et al. 2010; Long et al. 2021). However, the combined impacts of timber harvest and fire exclusion have resulted in higher densities of shrubs and small-diameter trees that increase fuel availability and continuity within younger stands, enhancing the risk of high-intensity fires (Stuart & Stephens 2006). Young stands also have more litter on the ground and a drier microclimate compared to older forests (Olson et al. 1990; Stuart & Stephens 2006). These conditions may interact with climate-driven changes such as warmer temperatures and increased drought, resulting in more frequent high-severity fires. While some fires may be capable of injuring or killing larger redwoods (Lorimer et al. 2009), the most significant changes are likely to occur within the sub-canopy and understory layers of the forest (Ramage et al. 2010; Mahdizadeh & Russell 2021). A recent survey of post-fire recovery from the 2020 CZU Lightning Fire Complex found that coast redwood in Big Basin Redwoods State Park exhibited very high survival rates (95%), especially compared to Douglas-fir (15%), which resulted in shifts in species composition within the forest sub-canopy (Mahdizadeh & Russell 2021).
- Although coast redwoods are typically resistant to **disease** (Olson et al. 1990), species-specific mortality in the mid-canopy and understory layers can significantly alter ecosystem composition and structure. In particular, sudden oak death, caused by the introduced pathogen *Phytophthora ramorum*, has become a significant concern in the region (Rizzo & Garbelotto 2003; Meentemeyer et al. 2004). Spread of sudden oak death is facilitated by host plants that support spore production, including California bay laurel and tanoak (Rizzo & Garbelotto 2003; Cobb et al. 2010, 2012). 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). Conversely, drier summer conditions could reduce disease prevalence by limiting growth of *P. ramorum* (Venette & Cohen 2006; Venette 2009).

  Sudden oak death has caused extensive tree injury and mortality in coastal forests (Davidson et al. 2003; Rizzo & Garbelotto 2003), with the highest rates of mortality occurring in tanoak,

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particularly among large trees (Cobb et al. 2012; Metz et al. 2012). Patterns of tanoak mortality have already caused shifts in species composition and sub-canopy structure in redwood stands with a high tanoak component (McPherson et al. 2010; Cobb et al. 2012; Metz et al. 2012). Although it is unlikely that tanoak will completely disappear from the forest due to its sprouting ability (Cobb et al. 2012; Metz et al. 2012), the presence of the *P. ramorum* pathogen is preventing tanoak from reaching maturity by repeatedly killing young trees (Ramage et al. 2011; Bowcutt 2014). Dense sprouts occur at the base of diseased trees after the main stem dies, which in many areas is resulting in dense understory conditions (Burns et al. 2016; Cunniffe et al. 2016). These thickets are likely to provide additional fuel for wildfires, and studies suggest that the presence of sudden oak death within a stand appears to increase post-fire mortality in both redwood and tanoak (Metz et al. 2013; Forrestel et al. 2015; Simler et al. 2017), especially in the middle stages of disease progression (Metz et al. 2013).

- **Increased frequency and/or severity of storm events** and associated wind damage and flooding may affect the structure and composition of coastal redwood forests, although these factors are not typically associated with redwood mortality (Lorimer et al. 2009). In fact, injuries to redwood branches during wind events can allow sprouting and the development of reiterated branches and trunks that are associated with the complex canopy structure that characterizes old-growth forests (Van Pelt et al. 2016; Sillett et al. 2018). However, more severe storms may be associated with increased windthrow, particularly in waterlogged soils (Olson et al. 1990; Lorimer et al. 2009).

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. Within coastal redwood forests, younger stands have already been degraded by a combination of historical timber harvest and fire exclusion, and as a result are also more sensitive to impacts from additional or ongoing non-climate stressors (Vuln. Assessment Worksheets, pers. comm., 2022).

- **Historical timber harvest** has significantly reduced the extent of old-growth forest areas within the GGB region, and has greatly altered composition and structure in logged areas that now make up the majority of coastal redwood forests in the area (Sawyer et al. 2000a; van Mantgem & Das 2014; Burns et al. 2018; Sillett et al. 2018). Second- and third-growth stands typically have very low structural complexity, with fewer large canopy trees, higher densities of small-diameter trees, and loss of understory diversity (van Mantgem & Das 2014; O'Hara et al. 2017). Forests that have been altered by logging are likely more vulnerable to moisture stress due to climate change, as the loss of large redwoods reduces fog capture and creates warmer, drier site conditions that may result in altered forest composition and enhanced fire risk (Olson et al. 1990; Dawson 1998; Mooney & Dawson 2016). Logging roads also cause significant erosion, resulting in soil loss within redwood stands and degradation of associated streams (Vuln.

Assessment Worksheets, pers. comm., 2022). Timber harvest continues today, both as a form of revenue from forest management activities (e.g., salvage logging) and also as an extractive industry in some parts of Santa Cruz County and northern portions of the GGB region (Vuln. Assessment Worksheets, pers. comm., 2022).

- **Fire exclusion and suppression** have altered historical fire regimes in coastal redwood forests, significantly increasing fire return intervals within the GGB region over the past 150 years (Baxter & Brown 2003; Stephens & Fry 2005; Davis & Borchert 2006). These changes have contributed to shifts in species composition as fast-growing species such as Douglas-fir and tanoak become more common in the mid-canopy layer (Burns et al. 2016) and fire-dependent shrub species in the understory decline (Vuln. Assessment Worksheets, pers. comm., 2022). As in most ecosystems in California, fire exclusion has also resulted in changes in fuel structure and increased fuel loading that increase the risk of more intense fires in the future (Lorimer et al. 2009). Second-growth forests are particularly vulnerable to intense fires due to increased tree and understory density (Lorimer et al. 2009; Burns et al. 2018). Fuel accumulation in adjacent ecosystems could also lead to high-intensity fires that spread more readily into redwood stands (Baxter & Brown 2003).
- Coastal redwood forests are relatively resistant to **invasion by non-native plant species** due to low light levels and relatively acidic soils under the forest canopy (Burns et al. 2016). However, invasion can occur within disturbed areas and canopy gaps (i.e., along roads and trails, on the forest edges), and species such as panic veldt grass (*Ehrharta erecta*) have become established within some areas of the GGB region, where they displace native redwood-associated understory species (Burns et al. 2016). In marginal habitats, such as on the southern edge of the coast redwood range, eucalyptus (*Eucalyptus* spp.) can also outcompete redwoods; however, this is unlikely to occur on more suitable sites (O'Hara et al. 2017). **Non-native pathogens** are also playing a significant role in altering ecosystem composition and structure within redwood forests of the GGB region, as sudden oak death results in significant mortality of tanoaks in the mid-canopy layer (Cobb et al. 2012; Metz et al. 2012).
- **Heavy recreational use** can increase soil compaction within coastal redwood forests, leading to root structure damage as well as damage and loss of herbaceous understory vegetation (Voigt 2016). Within the GGB region, these impacts have been observed within Muir Woods National Monument and Roy's Redwoods Preserve in Marin County (Vuln. Assessment Worksheets, pers. comm., 2022).
- **Dams and water diversions** reduce instream flows and alter flow variability (Asarian & Walker 2016), which impacts water availability and disrupts sedimentation processes that maintain alluvial stands (Vuln. Assessment Worksheets, pers. comm., 2022). Increases in severe and/or prolonged periods of drought together with expanding urban populations are likely to result in continued increases in future water demand, placing additional stress on existing water supplies (Medellín-Azuara et al. 2007).

Adaptive Capacity → Moderate *(high 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 (moderate confidence)

While coastal redwood forests are much more widespread in the region than many endemic communities, their distribution is limited to the coastal fog zone and within the GGB region they are primarily concentrated within cool, moist microclimates where soil moisture remains high enough to support the species (Olson et al. 1990; Burgess & Dawson 2004). Generally, coastal redwood forests have declined in both extent and integrity since Euro-American settlement in the region in the mid-1800s, with many remaining stands representing remnant populations (Burns et al. 2018). Old-growth forests, in particular, have been dramatically reduced as a result of logging, which has also significantly altered forest composition and structure within impacted areas that are now second-growth forests (Sawyer et al. 2000a; Burns et al. 2018). Remaining old-growth forests are highly fragmented, with significant losses of connectivity occurring among increasingly isolated patches (Burns et al. 2018; Vuln. Assessment Worksheets, pers. comm., 2022). However, a large proportion of coastal redwood forests within the region are now protected as public lands or through various open space designations (Vuln. Assessment Worksheets, pers. comm., 2022).

Coast redwood seeds have low viability rates and short dispersal distances, so seedling recruitment is relatively low in this species (Olson et al. 1990; Mooney & Dawson 2016). Dispersal can be limited by factors such as continued land-use conversion to development and agriculture, as well as some topographic and geographic features that influence site suitability such as slope, elevation, and soil type (Vuln. Assessment Worksheets, pers. comm., 2022). Models suggest that drier future conditions or reductions in the frequency of coastal fog would significantly reduce climatic suitability for this species, particularly within the GGB region where it is already limited by moisture stress (Johnstone & Dawson 2010; Fernández et al. 2015; Ackerly et al. 2020; Sillett et al. 2022). The potential for northward migration is unknown; however, their dependence on the relatively narrow coastal zone where fog occurs may make migration difficult (Vuln. Assessment Worksheets, pers. comm., 2022).

Ecosystem diversity → Moderate (high confidence)

Coast redwood is the foundation species within this forest type, dominating the canopy due to its great height and longevity (Olson et al. 1990; Sawyer et al. 2000b; Van Pelt et al. 2016) and creating microclimates that support understory species adapted to cool, moist, low-light conditions (Mooney & Dawson 2016). Old-growth forests have high spatial and structural complexity in tree stems and crowns, which is created by small-scale disturbances that damage tree branches and stimulate trunk iterations and limb formation (Van Pelt et al. 2016; Sillett et al. 2018). Younger forests with a history of logging, on the other hand, are typically dense with low structural complexity and associated biodiversity, increasing their vulnerability to environmental stressors and disturbances (Burns et al. 2018; Vuln. Assessment Worksheets, pers. comm., 2022).

Although species richness is lower compared to many other forest types in California, coastal redwood forests support many species that occupy specialized habitat niches, including understory plants as well as epiphytes growing in the forest canopy, along with a variety of mammals, birds, amphibians, and invertebrates (Cooperrider et al. 2000; Mooney & Dawson 2016). Structural characteristics within old-growth forests, in particular, are associated with many rare species or those that depend on specific habitat characteristics (e.g., snags, downed logs, complex crown structure), such as the marbled murrelet (*Brachyramphus marmoratus*) and northern spotted owl (*Strix occidentalis*; Cooperrider et al. 2000; Mooney & Dawson 2016). Redwood stands are often situated adjacent to streams that support threatened and endangered salmonids, including coho (*Oncorhynchus kisutch*) and steelhead (*O. mykiss*; Burns et al. 2016).

Resistance and recovery → High (high confidence)

Coastal redwood forests are able to recover rapidly from wildfire and other disturbances because both redwood and tanoak can resprout following injury or topkill (Lorimer et al. 2009; Ramage et al. 2010; Lazzeri-Aerts & Russell 2014). Redwood has a competitive advantage over other species due to its greater fire resistance, prolific sprouting, and rapid growth (Lorimer et al. 2009; Ramage et al. 2010; Lazzeri-Aerts & Russell 2014; Mahdizadeh & Russell 2021), with the greatest fire resistance and sprouting rates occurring in the largest and tallest trees (Mahdizadeh & Russell 2021). Redwoods are also naturally resistant to insect and fungal infestations due to high levels of tannins in their bark, and invasive plants struggle to become established within the acidic soils and low light levels of the forest understory (Burns et al. 2016). These factors, together with their extremely long lifespan (over 2,000 years; Sillett et al. 2015), have contributed to the persistence of this forest type in the region for millennia (Sawyer et al. 2000a). The longevity of the species suggests that coastal redwood forests tolerate a wide range of climate conditions and disturbance regimes and will likely continue to persist over the coming centuries, allowing them to serve as climate refugia for many species (Fernández et al. 2015; O'Hara et al. 2017; Vuln. Assessment Worksheets, pers. comm., 2022). However, low rates of sexual reproduction in coast redwood does reduce opportunities for species migration or genetic shifts towards more adaptive traits (Fernández et al. 2015; O'Hara et al. 2017).

Management potential → Moderate (high confidence)

Support for climate-informed management of coastal redwood forests is high due to their significant public and societal value, which is recognized worldwide (Noss et al. 2000; Burns et al. 2018). Coast redwood is an emblematic species, with old-growth stands in particular serving as a symbol for larger conservation issues such as the importance of forest protection (Vuln. Assessment Worksheets, pers.

comm., 2022). These forests are also highly valued for public recreation, and organizations such as the Sempervirens Fund and Save the Redwoods League draw significant support for the conservation and management of these unique ecosystems (Vuln. Assessment Worksheets, pers. comm., 2022). In 2013, the coast redwood was listed as endangered by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Farjon & Schmid 2013), though this listing was somewhat controversial as the species is not as rare or rapidly declining as most others with this designation (Vuln. Assessment Reviewer, pers. comm., 2023). The Redwood Forest and Woodland vegetation alliance is also considered a Sensitive Natural Community by the California Department of Fish and Wildlife, which is tied to requirements for consideration within environmental review processes such as CEQA (CDFW 2023). As a result of the significant conservation efforts that have occurred, most old-growth stands in the region have been protected within parks, experimental forests, and private reserves (Mooney & Dawson 2016; Burns et al. 2018). Heritage tree ordinances can protect individual high-value trees, and larger numbers are often protected through open space designation (Vuln. Assessment Worksheets, pers. comm., 2022).

Management of coastal redwood forests in the context of climate change is challenging, largely because the measures required to significantly increase resilience to cumulative impacts are costly, particularly for larger landscape- or population-scale efforts (Vuln. Assessment Worksheets, pers. comm., 2022). However, continuing efforts to protect existing old-growth coastal redwood forests are critical, both because large, mature trees are more resistant to changing climate conditions and disturbances (e.g., fire, drought, insects, and disease) (Mooney & Dawson 2016) but also because of the role that coast redwoods can play in climate mitigation through carbon sequestration and storage (Sillett et al. 2020; Soland et al. 2021). Protecting forests and prioritizing stewardship in areas where projected climate conditions are expected to remain within or close to the suitable range for coast redwood would provide refugia and increase connectivity for many rare or endemic species threatened by climate change (DellaSala et al. 2018). Protection efforts should also consider biologically-significant second-growth forests that represent the natural range of variability within this habitat type, particularly those that connect existing intact forest patches (Noss et al. 2000). In degraded second-growth forests, the scientific literature supports several management strategies that may enhance or restore ecosystem functioning, accelerate the development of old-growth forest characteristics, and increase resilience to future climate changes (Noss et al. 2000; DellaSala et al. 2018). These include thinning in second- or third-growth stands to open up the canopy, reduce potential fuels, and increase structural diversity (van Mantgem & Das 2014; Dagley et al. 2018; Prichard et al. 2021; Soland et al. 2021; Brodie et al. 2023), strategic crown injury to increase structural complexity (Sillett et al. 2018), and reintroduction of low- to moderate-intensity fire through prescribed burns (Thornburgh et al. 2000; Jones & Russell 2015; Prichard et al. 2021; Brodie et al. 2023). Managing coastal redwood forests to mitigate the threat of sudden oak death is also important, though challenging due to the lack of effective management strategies for eradication or active suppression at larger spatial scales (Swiecki et al. 2017).

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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