Southern California Oak Woodland Habitats
Climate Change Vulnerability Assessment Synthesis

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for oak woodland habitats based on expert input and existing information. Specifically, the information presented below comprises habitat expert vulnerability assessment survey results and comments, peer-review comments and revisions, and relevant references from the literature. The aim of this document is to expand understanding of habitat vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.*


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Executive Summary

As defined by the California Wildlife Habitat Relationships System (CWHR), the southern California study region contains primarily coastal oak woodlands and montane hardwoods, with coast live oak dominating the former (CWHR 2015a), and black oak and canyon live oak dominating the latter (CWHR 2015b). Engelmann oak, interior live oak, scrub oak, and other species can co-occur with these dominants in oak canopies (Bartolome 1987; CWHR 2015a, 2015b, 2015c, 2015d), and many oak species occur as sub-dominants in other habitat types (Los Angeles County 2011). The northern zones of the study area also contain blue oak and valley oak woodlands, which reach the southern end of their distribution in this region (CWHR 2015c, 2015d; Hoagland et al. 2011; Plumb and McDonald 1981). As dominant canopy species, oaks create favorable microclimates for diverse understory vegetation and provide habitat for many wildlife species (Howard 1992; Tietje et al. 2005; Verner 1987).

The relative vulnerability of oak woodland habitats in southern California was evaluated to be low-moderate[1] by habitat experts due to low-moderate sensitivity to climate and non-climate stressors, low-moderate exposure to projected future climate changes, and moderate adaptive capacity.

Sensitivity and Exposure	Climate sensitivities: Precipitation, soil moisture Disturbance regimes: Wildfire, disease Non-climate sensitivities: Invasive & other problematic species, land use conversion/development

Shifts in precipitation and soil moisture are likely to affect oak woodland distribution, composition, growth, and recruitment, and impacts may be compounded by shifts in temperature and drought frequency and intensity. Although oaks are adapted to wildfire, shifts in wildfire frequency and intensity may affect oak recruitment and survival. Several oak species are vulnerable to sudden oak death, but it is not currently extensive in southern California,

[1] Confidence: High

although wetter conditions could facilitate future spread. Invasive plant species compete with oak seedlings for soil moisture, while invasive insects (e.g., goldspotted oak borer, polyphagous shot hole borer) are contributing to high oak mortality within the study region, and may expand with climate change. Land-use conversion has altered the extent and continuity of oak woodland habitat, and continues to threaten this system by facilitating invasive species introductions, increasing wildfire ignition risk, and eliminating potential refugia.

Adaptive Capacity	Habitat extent, integrity, and continuity: Moderate geographic extent, low-moderate integrity (partially degraded), moderate continuity Resistance and recovery: Moderate resistance and recovery potential Habitat diversity: Moderate overall diversity Management potential: High societal value, low-moderate management potential

Oak woodland habitat has been altered and fragmented as a result of agriculture and development, and habitat structure is being affected by exotic annual grass invasions. Oaks are long-lived species with variable recruitment and limited migration potential, making it difficult for these species to keep pace with projected climate changes. Canopy diversity is fairly low, and as keystone species, loss of oak canopy species would eliminate or cause severe changes in oak woodland habitat. Oak woodlands provide a variety of ecosystem services (e.g., biodiversity, recreation, carbon sequestration). Potential management options identified by habitat experts largely deal with enhancing oak recruitment and managing non-climate stressors that may exacerbate climate impacts (e.g., invasive species).

Sensitivity

The overall sensitivity of oak woodland systems to climate and non-climate stressors was evaluated to be low-moderate by habitat experts.[2]

Sensitivity to climate and climate-driven changes

Habitat experts evaluated oak woodland habitats to have low-moderate sensitivity to climate and climate-driven changes,[3] including: precipitation and soil moisture.[4] Habitat experts also identified drought as an important stressor for oak woodland habitats.[5] Although not ranked as a significant climate stressor by habitat experts, the scientific literature also identified air temperature as an important factor to consider for oak woodland habitats.

Precipitation, soil moisture, and temperature

Precipitation, soil moisture, and temperature largely influence oak distribution and vegetation associations (Table 1; Kueppers et al. 2005; McLaughlin and Zavaleta 2012; Waddell and Barrett 2005). Blue oak systems are well adapted to dry, hilly terrain where groundwater is typically unavailable (Gaman and Firman 2006; Ritter 1988a; Waddell and Barrett 2005). In contrast,

[2] Confidence: Moderate
[3] Confidence: High
[4] Factors presented are those ranked highest by habitat experts. A full list of evaluated factors can be found at the end of this document.
[5] Not all habitat experts agreed on this factor.

valley oak systems are found in valley bottoms away from the main fog zone and frequently utilize groundwater (Ritter 1988b). Relative to blue and valley oak woodlands, coastal oak and montane hardwood systems persist in more mesic Mediterranean climates and are generally established in coastal areas (Holland 1988; McDonald 1988).

Table 1. Average minimum and maximum summer (S) and winter (W) temperatures, average annual precipitation, and geographic distribution of CWHR coastal oak woodland (CWHR 2015a; Holland 1988), montane hardwood (CWHR 2015b; McDonald 1988), blue oak (CWHR 2015c; Ritter et al. 1988a), and valley oak woodland (CWHR 2015d; Ritter et al. 1998b) ecosystems in southern and central coast California.[6]

Woodland Type	**Temperature (°C)**	**Precipitation (cm)**	**Geographic distribution in study area and elevation**
Coastal oak woodland	S: 24-36 W: 2-7	38-100	Coastal foothills and valleys of the central coast and southern California regions (0-1,525 m)
Montane hardwood woodland	S: 20-25 W: 3-7	91-279	Upper elevations (100-2,745 m)
Blue oak woodland	S: 24-36 W: 2-6	51-102	Foothills of Transverse, Peninsular, and Coast Ranges (76-1,370 m)
Valley oak woodland	No explicit data	14-203	Valley bottoms adjacent to Tehachapi Mountains and Coast Range (0-610 m)

Within these broad woodland associations, moisture gradients drive spatial species organization. Coast live oaks (*Quercus agrifolia*) typically reside in mesic areas due to slow germination, including canyon bottoms, north slopes, and areas with deeper soils (Steinberg 2002 and citations therein). Canyon live oaks (*Quercus chrysolepis*) are also common on north-facing slopes, and Engelmann oaks (*Quercus engelmannii*) cluster near vernal pools (Vulnerability Assessment Reviewers, pers. comm., 2015). Similarly, valley oaks (*Quercus lobata*) are selective of soil type and location, as they require root access to permanent groundwater sources (Ritter 1988b).

Moisture availability, influenced by rainfall, competition, soil texture, and evaporative stress (Plumb and De Lasaux 1997; Plumb and Hannah 1991; Plumb and Kraus 1991), drives oak survival, fitness, and habitat distribution. In documented habitat shifts in response to climate change, valley oak saplings have been found to cluster in areas with high water availability, which likely ameliorates drought stress (McLaughlin and Zavaleta 2012). In general, drier conditions have been linked with oak mortality and habitat contractions in several southern California study sites (Hayes and Donnelly 2014 [valley oak]; Principe 2002 [Engelmann oak]). In addition, research has shown that young oaks have a narrower climatic envelope than adults; they are more sensitive to warmer temperatures (McLaughlin and Zavaleta 2012) and moisture stress (Matzner et al. 2003) than mature trees. Warmer and drier conditions associated with climate change may reduce suitable germination and growth periods, affecting oak woodland recruitment and distribution.

[6] See the Habitat Diversity section for an overview of species present in these different oak woodland types.

Precipitation, soil moisture, and temperature affect oak recruitment in the following ways:

Acorn production

Acorn production is likely correlated with weather (Koenig et al. 1996), and varies widely between years (Koenig et al. 1994, 1999; Plumb and McDonald 1981). In a study in the central Coast Range, Koenig et al. (1996) found that large acorn crops in evergreen oak species (coast live oak and canyon live oak) were correlated with higher rainfall in the 1-2 years prior to crop production. In the same study, the largest acorn crops in deciduous oak species (blue oak [*Quercus douglasii*] and valley oak) occurred in years with the warmest mean April temperatures, which contributed to favorable pollination and fertilization conditions (Koenig et al. 1996). Indirectly, acorn production variability may impact oak dispersal by affecting food availability for wildlife. Many wildlife species act as key dispersal agents for oak species (McDonald 1990; McDonald and Tappeiner 1996), and food-driven reductions in wildlife populations could affect future oak migration potential in the face of climate change (Vulnerability Assessment Reviewers, pers. comm., 2015).

Acorn germination and seedling emergence

Acorn germination typically coincides with seasonal winter rains (Plumb 1982; Steinberg 2002; Tyler et al. 2008), although favorable oak germination and growth conditions are quite specific. Following high acorn production, several years of abundant annual rainfall and average to below average temperatures are essential for successful seedling emergence and survival (Z. Principe, pers. comm., 2015). Germination moisture requirements also vary by species (Snow 1991). For example, in laboratory studies, Snow (1991) found that Engelmann oaks are less dependent on moisture for germination than coast live oaks. During dry years oak seedling emergence and survival can be very low (Griffin 1971; Plumb and Hannah 1991; Principe 2002; Tyler et al. 2008). However, shade provided by nurse plants (Tyler et al. 2006) and intact mature oak canopies (Matzner et al. 2003; Muick 1991; Plumb and Hannah 1991) can create favorable microsites for emergence and seedling survival, even under dry conditions (Plumb and Hannah 1991; Tyler et al. 2006).

<u>Drought</u>

Many oak species are resilient to short-term drought events and feature adaptations to accommodate seasonal summer drought (Howard 1992; Principe 2002; Steinberg 2002), including winter growth periods (Steinberg 2002 [coast live oak]), rapid acorn germination (Principe 2002 [Engelmann oak]), rapid seedling growth early in the season (Matzner et al. 2003 [blue oak]), and drought deciduousness (Pavlik et al. 1991 cited in McCreary 2004 [blue oak]; Snow 1991 [Engelmann oak]). However, oak woodlands are generally sensitive to prolonged drought periods, and drought sensitivity varies amongst oak species and age classes. Coast live oak may be particularly vulnerable (Steinberg 2002); it has been found to exhibit less adaptive root growth in response to simulated drought conditions (i.e., reduced soil moisture) than valley and blue oak (Callaway 1990). Valley oak may also be sensitive to drought periods that lower water tables, as reduced access to groundwater can negatively impact mature trees (Griffin 1973; Howard 1992). Drought may also impair Engelmann oak seedling and sapling recruitment (Principe 2015, 2002) and blue oak seedling growth and survival (Matzner et al. 2003). Significant oak mortality and dieback related to drought is currently being experienced in the southern California study region (Vulnerability Assessment Reviewers, pers. comm., 2015).

Sensitivity to disturbance regimes

Habitat experts evaluated oak woodland habitats to have low-moderate sensitivity to disturbance regimes,[7] including: wildfire and disease.[8,9] Habitat experts also indicated that insects affect this habitat.[10] The scientific literature identified herbivory as an additional disturbance regime affecting oak woodland regeneration.

Wildfire

Wildfire is an essential driver of succession in California's oak woodland ecosystems (Lathrop and Osborne 1991; McCreary 2004; Plumb and McDonald 1981), influencing species composition, form, and density (Plumb and McDonald 1981). Historically, intervals between fires (both natural and human-ignited) in oak woodland habitats ranged from 30-50 years with major fires occurring every 40-100 years (Pavlik et al. 1991 cited in McCreary 2004). Due to their coevolution with fire, oak woodland ecosystems have adopted mechanisms to survive periodic burning (McCreary 2004), including thick bark that insulates the cambium from heat, and the ability to resprout following fire (Plumb and Gomez 1983). Resprouting has been documented in Engelmann oaks, coast live oaks, valley oaks, canyon live oaks, interior live oaks (*Quercus wislizeni)*, black oaks (*Quercus kelloggii*), and scrub oaks (Howard 1992; Lathrop and Osborne 1991; McDonald 1990; Montalvo et al. 1997; Paysen and Narog 1993; Plumb and Gomez 1983).

Fire vulnerability varies by oak species (Plumb and Gomez 1983; Plumb and McDonald 1981) and by tree age and size. Bark thickness and the proportion of dead and live bark influences heat protection conferred by bark, resulting in differential susceptibility to burn injury between species (Plumb and Gomez 1983). For example, coast live oak typically experiences less fire damage than other oak species (e.g., scrub oak; Plumb and Gomez 1983; Plumb and McDonald 1981). Mature oaks may survive low-intensity fires with minimal damage due to higher canopies and thicker bark (Howard 1992; Lathrop and Osborne 1991; Plumb and Gomez 1983; Principe 2015, 2002*;* Steinberg 2002), unless high fuel build-up acts as ladder fuel between the ground and canopy (Lathrop and Osborne 1991; Principe 2015). Smaller oaks, including seedlings and scrub oaks, are more vulnerable to fire than larger individuals (Plumb and Gomez 1983; Principe 2002).

Due to a combination of higher fuel loads as a result of fire suppression and increased invasive species establishment, and increased anthropogenic ignitions as a result of regional population growth, oak woodlands are now experiencing more frequent, severe, and larger fires relative to

[7] Confidence: Low

[8] Factors presented are those ranked highest by habitat experts. A full list of evaluated factors can be found at the end of this document.

[9] Not all habitat experts agreed on these disturbance regimes.

[10] Not all habitat experts agreed on this disturbance regime.

the historical regime (McCreary 2004). Shorter fire return intervals are correlated with low sapling recruitment (Swiecki and Bernhardt 1998), and when combined with increasing fire severity and incidence of crown fires, can damage or cause mortality of mature oaks (Howard 1992; Paysen and Narog 1993; Principe 2002). For example, Principe (2015) found that Engelmann oaks with basal fire scars from previous burns experienced higher subsequent fire mortality than previously unburned trees. Shorter fire return intervals can also eliminate tree mast, remove topsoil through wind and water erosion (McCreary 2004), and/or create harsh soil surface conditions by removing leaf litter (Principe 2002), affecting recruitment and potentially facilitating shifts to more fire-adapted vegetation types (Plumb and McDonald 1981).

Burn seasonality also influences oak damage and recovery (Lathrop and Osborne 1991; Paysen and Narog 1993; Plumb and Gomez 1983; Principe 2002). Seedling and sapling survival may be lower following spring burns compared to fall burns, as spring resprouts must grapple with seasonal summer drought conditions (Lathrop and Osborne 1991). However, spring burns may also undermine seed production in invasive annual grasses, reducing overall competition for soil moisture (Principe 2002 and citations therein). Comparatively, fall burns may cause more damage, depending on the site condition and species present (Plumb and Gomez 1983), as depleted fuel moisture can contribute to hotter burns (Principe 2002).

Post-fire oak recovery is influenced by a variety of factors (Plumb and Gomez 1983), including species (Plumb and Gomez 1983; Plumb and McDonald 1981), pre-fire tree size (Plumb and Gomez 1983; Principe 2002), and fire damage to tree (Plumb and Gomez 1983; Principe 2015). Different oak species exhibit variable post-fire recovery abilities (Plumb and Gomez 1983); for example, coast live oak resprouts much more readily than Engelmann oak (Vulnerability Assessment Reviewers, pers. comm., 2015). Fire damage also affects recovery; in a study on the Santa Ysabel Open Space Preserve, Engelmann oaks experiencing severe fire damage exhibited basal resprouting, while individuals experiencing low damage exhibited crown resprouting, resulting in altered habitat structure post-fire in severe burn areas (Principe 2015).

Insects and disease

Oaks are sensitive to both insect and disease outbreaks (Jimerson and Carothers 2002; Rizzo et al. 2002), especially introduced varieties, which may become significant in the future (Coleman and Seybold 2008). For example, the recent emergence (circa 2002) of the non-native goldspotted oak borer (*Agrilus auroguttatus;* GSOB) has caused mortality of over 25,000 oaks in San Diego, Riverside, and Orange Counties, including on the Cleveland National Forest (Coleman et al. 2011, 2015; Coleman and Seybold 2008; Haavik et al. 2015; University of California Cooperative Extension 2015). GSOB affects mature coast live oak, canyon live oak, and black oak, causing crown dieback and tree mortality as larvae feed on oak phloem, xylem, and cambium (Coleman and Seybold 2008). GSOB may also exacerbate drought stress in infected trees (Coleman et al. 2011). GSOB has also been documented in Engelmann oaks (Coleman and Seybold 2008), but has not been directly tied with tree mortality in this species (Coleman et al. 2015). This pest was not previously known to feed on *Quercus* spp. of the California region, and as the GSOB expands northward, whether through natural migration and/or human-facilitated movement via firewood, it may also begin to affect interior live oak and other *Quercus* communities (Coleman et al. 2011, 2015; Coleman and Seybold 2008). Experts predict that increasing temperatures will not impede, or may even benefit, the proliferation of GSOB within the study area (Z. Principe, pers. comm., 2015). Much of California is projected to be climatically suitable for the GSOB in the future, increasing the likelihood of pest expansion from its current range (Coleman et al. 2015).

In addition, the polyphagous shot hole borer (*Euwallacea* sp.[11]; PSHB) and the proliferation of its associated fungus (*Fusarium euwallacea*) may pose a substantial risk to oak communities in southern California. Mortality associated with this insect-fungus pairing, commonly known as Fusarium dieback, has been documented on several non-oak host plants in Los Angeles and Orange Counties, and spread to oak communities is possible. Coast live oaks serve as a reproductive host for this species, and coast live oak, canyon live oak, and valley oak are vulnerable to Fusarium dieback (Eskalen et al. 2013).

Sudden oak death, caused by the introduced pathogen *Phytothphthora ramorum*, affects oaks in coastal and montane forests of California (Rizzo et al. 2002), although it is not as widespread in the southern California study region as in northern portions of the state (Coleman and Seybold 2008 and citations therein). Moisture is essential for survival and sporulation of *P. ramorum*, and the duration, frequency, and timing of rain events during winter and spring play a key role in inoculum production. Heavy late-spring rain associated with El Niño events (e.g., 1998) may have played a critical role in the current distribution of *P. ramorum* in California. Increases in winter rain may produce optimal conditions for the pathogen in some areas, and models project future oak infection risk to be moderate (Meentemeyer et al. 2004). Other tree diseases are also appearing in southern California oak woodlands due to population growth and nursery stock movement within the region, increasing the potential for future disease issues amongst regional oak woodlands (Vulnerability Assessment Reviewers, pers. comm., 2015).

Herbivory

Several studies identify herbivory of acorns, seedlings, and saplings by deer, rodents, and insects as a major source of oak mortality and reduced recruitment (Hall et al. 1992; Plumb and De Lasaux 1997; Plumb and McDonald 1981; Tyler et al. 2008). Sensitivity to herbivory varies by life stage and species (Griffin 1976; Principe 2002 and citations therein; Tyler et al. 2008). Shrubs and other nurse plants may buffer herbivory impacts (Tyler et al. 2006). Herbivory may exacerbate climate-driven changes in oak recruitment and establishment, and interact with other non-climate stressors (i.e., livestock grazing, invasive species competition, habitat fragmentation) to affect oak survival and migration potential in response to changing conditions (Conlisk et al. 2012; Howard 1992 and citations therein; Moore and Swihart 2007).

In addition, herbivore population numbers are likely sensitive and may shift in response to climate change and/or altered landscape conditions, although exact responses are uncertain (Conlisk et al. 2012). For example, drought conditions may reduce available forage and depress

[11] The specific identity of this beetle is not yet known (Eskalen et al. 2013)

rodent populations (U.S. Fish and Wildlife Service 1998) and/or increase ungulate use of riparian oak woodland zones (Bright and Hervert 2005; Gogan and Barrett 1987). Additionally, shifts in apex predator abundance may cause trophic cascades, affecting oak herbivory pressure; for example, black oak recruitment declines in Yosemite National Park over the past century are linked with reductions in mountain lion populations and associated increases in mule deer populations and oak herbivory (Ripple and Beschta 2008).

Sensitivity and current exposure to non-climate stressors

Habitat experts evaluated oak woodland habitats to have moderate sensitivity to non-climate stressors,[12] with an overall moderate exposure to these stressors within the study region.[13] Key non-climate stressors identified for oak woodland habitats include invasive and other problematic species and land-use conversion.[14] Habitat experts evaluated exposure to these stressors to be geographically localized. The scientific literature also identified livestock grazing as an additional non-climate stressor affecting oak woodland habitats, but regional habitat experts indicated that livestock grazing is not as significant of a stressor in southern California compared to the rest of the state. Non-climate stressors may interact with climate change to affect oak regeneration and resilience to changing conditions (Hayes and Donnelly 2014).

Invasive and problematic species

Non-native species, particularly exotic annual grasses (e.g., *Bromus* spp.), can inhibit oak germination, seedling growth, and seedling survival by competing for soil moisture (Danielsen and Halvorson 1991; Gordon and Rice 2000; Plumb and De Lasaux 1997) and other resources (e.g., space, nutrients, light; Principe 2002). Invasive grasses also exacerbate shifting fire regimes in oak woodland habitats (Principe 2002). Oak woodlands are also very vulnerable to invasive insects (e.g., GSOB, PSHB; see discussion in Disturbance Regime section). Invasive species spread is largely facilitated by livestock grazing and recreation (e.g., campers transporting contaminated firewood; Vulnerability Assessment Reviewers, pers. comm., 2015).

Land-use conversion

Oak woodland habitats, the majority of which occur on private lands (Davis et al. 1998), are vulnerable to urban, suburban, and rural development and agricultural conversion, especially at lower elevations where they are adjacent to existing development (Jimerson and Carothers 2002; Los Angeles County 2011). In a study comparing 2005 California vegetation mapping data with regional development trends, Gaman and Firman (2006) estimate that 20% of southern California's native oak woodland habitat has been developed and an additional 10% is at risk of development by 2040. Development rates for oak woodland habitat in southern California are the highest of the entire state (Gaman and Firman 2006).

[12] Confidence: Moderate
[13] Confidence: High
[14] Factors presented are those ranked highest by habitat experts. A full list of evaluated factors can be found at the end of this document.

Land-use conversion destroys and fragments habitat, affecting gene flow through pollen movement, which may impact recruitment by increasing reproductive isolation and associated negative effects (Los Angeles County 2011; Sork et al. 2002). One study of blue oaks indicates that such land-use conversion impacts are irreversible (Swiecki and Bernhardt 1998). Land-use conversion can also influence oak habitat resilience to climate impacts by affecting available microrefugia, altering resource availability (e.g., surface and groundwater; Garcia et al. 1991; Hayes and Donnelly 2014), and/or creating undesirable edge effects (Los Angeles County 2011). Additionally, urban encroachment may increase ignition potential, exacerbating shifting fire regimes in oak woodland habitats (Conlisk et al. 2012; Syphard et al. 2007).

Livestock grazing

Along with wildlife and insect herbivory, livestock grazing may affect oak woodland recruitment and establishment. Livestock grazing can cause mortality through direct herbivory of acorns, seedlings, or saplings (Hoagland et al. 2011; Principe 2002), and affect adult tree condition (Hoagland et al. 2011). Grazing impacts on oak woodlands likely vary according to grazing intensity, timing, vegetation composition, and other factors (Hoagland et al. 2011; Tyler et al. 2008). For example, grazing by livestock and wildlife in both spring and summer is associated with significantly lower seedling survivorship than grazing in winter alone (Hall et al. 1992). Alternatively, livestock grazing can facilitate oak seedling recruitment by reducing competition from non-native grasses (Hoagland et al. 2011; Tyler et al. 2008) and/or by reducing herbaceous cover that attracts rodent and insect herbivores (Tyler et al. 2008). Livestock also affect oak ecosystems non-consumptively by altering soil infiltration, compaction, and runoff and erosion patterns (Hauptfeld and Kershner 2014; Hoagland et al. 2011; Jimerson and Carothers 2002; Principe 2002). Relative to land-use conversion, grazing is less of a threat to oak woodlands in southern California compared to other areas of the state (Vulnerability Assessment Reviewers, pers. comm., 2015).

Future Climate Exposure

Habitat experts evaluated oak woodland habitats to have low-moderate exposure to projected future climate and climate-driven changes,[15] and key climate variables to consider include: increased air temperature and extreme high temperature events, precipitation changes, increased wildfire, and decreased soil moisture (Table 2).[16,17] Habitat experts also identified increased drought as an important factor to consider for this habitat (Table 2).[18] For a detailed overview of how these factors are projected to change in the future, please see the Southern California Climate Overview (http://ecoadapt.org/programs/adaptation-consultations/socal). Habitat experts indicated that refugia areas for oak woodland habitats may occur at higher

[15] Confidence: High

[16] Factors presented are those ranked highest by habitat experts. A full list of evaluated factors can be found at the end of this document.

[17] Habitat experts identified these key factors, but did not provide any additional comments, and no supporting information about future changes in endemic habitats in response to these factors could be found in the literature.

[18] Not all habitat experts agreed on this factor.

elevations, as well as in areas with abundant moisture (Vulnerability Assessment Reviewers, pers. comm., 2015).

Table 2. Anticipated oak woodland habitat response to climate and climate-driven changes.

Climate and climate-driven changes	Anticipated oak woodland response
Precipitation and soil moisture *Variable annual precipitation volume and timing, with wetter winters and drier summers; increased climatic water deficit*	• Increased tree moisture stress and associated mortality • Variable acorn production and germination • Reduced seedling and sapling recruitment • Restricted growth (all life stages) • Shifts in disease vulnerability • Distribution shifts and/or shifts in dominant oak canopy species: ○ Blue oak and valley oak: northward and upward distributional shift, cluster around moist microrefugia ○ Montane hardwood and coastal oak: potential range contraction
Drought *Longer, more severe droughts with drought years twice as likely to occur*	• Increased mortality (all life stages) • Reduced seedling emergence and growth • Reduced sapling and mature tree growth • Range contraction for mesic oak species
Air temperature and extreme heat events *+2.5 to +9°C by 2100; heat waves, particularly humid nighttime heat events, will occur more frequently, last longer, and feature hotter temperatures*	• Increased vulnerability to insects (e.g., goldspotted oak borer) • Potential habitat contractions if seedling/sapling thermal tolerance is exceeded
Wildfire *Increased fire size, frequency, and severity*	• Increased oak mortality (all life stages) • Reduced recruitment • Less hospitable soil germination sites due to litter removal

<u>Precipitation and temperature</u>

Altered precipitation patterns may have substantial effects on oak woodland distribution, composition, and recruitment in southern California (Kueppers et al. 2005), while increasing temperatures will likely exacerbate moisture stress and drought risk and severity (Griffin and Anchukaitis 2014). Microrefugia at both the local and landscape scale, including areas with higher water availability, may play an important role in tempering the effects of regional climate change on oak woodland habitats (McLaughlin and Zavaleta 2012).

<u>Wildfire</u>

In a modeling study by Conlisk et al. (2012), fire frequency played a significant role in determining Engelmann oak survival. Under various future climate scenarios, shorter fire return intervals (i.e., 20 and 60 years) were modeled to lead to significant losses of Engelmann oak individuals by 2100 (Conlisk et al. 2012).

<u>Species distributions</u>

Many oak woodland habitats are projected to experience range contractions and distribution shifts in response to climate warming (see specific projections below). However, as slow-growing species with limited dispersal potential, it is unknown whether oak species will be able to track projected shifts in climate (Conlisk et al. 2012; McLaughlin and Zavaleta 2012; Sork et al. 2010).

Coastal oak woodlands

The combined impact of climate change and anthropogenic forcing has led to poor future projections for two of southern California's distinctive oak trees: coast live oak and Engelmann oak. Specifically, Principe et al. (2013) project that, based on anticipated temperature increases by mid-century, only 28% and 46% of the current distribution of coast live oak and Engelmann oak, respectively, will persist within areas of thermal refugia. Most losses of coast live oak distribution will occur in the San Diego foothills and mountains and interior Riverside mountains, with areas of refugia occurring in the Santa Ana Mountains and in small portions of the San Diego mountains. Engelmann oak is projected to persist in the San Diego and Santa Ana Mountains while contracting from lower elevations and foothills (Principe et al. 2013). Areas with elevated soil moisture and reduced water stress may act as refugia (Z. Principe, pers. comm., 2015). Similarly, Conlisk et al. (2012) modeled a loss of Engelmann oaks and suitable Engelmann oak habitat in future scenarios defined by drier conditions and increased fire frequency. Dispersal, fire, and masting all contributed variably to reduced Engelmann oak abundance, which Conlisk et al. (2012) project to decline 39-67% by 2100. Conlisk et al. (2012) project that along with abundance declines, Engelmann oak distribution will likely shift southeast to higher elevations within San Diego County by 2100.

Shrub associates of coastal oak woodlands have variable future modeled habitat distribution. Poison oak (*Toxicodendron diversilobum*) is projected to fare the worst, with only 35% of current distribution projected to be in thermal refugia by mid-century; shifts in poison oak mirror distribution shifts of coast live oak. Hollyleaf cherry (*Prunus ilicifolia*), hollyleaf redberry (*Rhamnus ilicifolia*), chaparral currant (*Ribes malvaceum*), and toyon (*Heteromeles arbutifolia*) are projected to have 63%, 79%, 99%, and 85%, respectively, of current habitat in future thermal refugia by mid-century (Principe et al. 2013).

Valley oak, blue oak, and black oak woodlands

Changes in temperature, precipitation, and soil moisture have also been predicted to shift the distribution of blue oak and valley oak woodlands. Modeling by Kueppers et al. (2005) projects that suitable habitat for blue oak woodlands and valley oak woodlands will contract to 59% and 54%, respectively, by late century, with warmer and drier conditions, with suitable habitat moving northward in latitude and upward in elevation. Similarly, modeling by Hoagland et al. (2011) projects a decline in climatic habitat suitability for blue, valley, and black oak woodlands on Tejon Ranch by mid- and late-century, as well as shifts in dominant oak species in existing habitat areas. Tejon Ranch oak habitats are largely projected to shift to higher elevations and north-facing aspects (Hoagland et al. 2011). Statewide modeling by The Nature Conservancy indicates similar patterns, with blue oak, black oak, and valley oak projected to have only 10%, 48%, and 13% of current habitat in thermal refugia by late century, and foothill pine (*Pinus* *sabiniana*) and California buckeye (*Aesculus californica*) to have only 27% and 35% of current habitat in refugia over the same time frame (Principe et al. 2013). For all of these species, habitat loss was projected at lower elevations, with moderate habitat expansion in higher elevation areas (Principe et al. 2013). However, microrefugia may exist on many landscapes, buffering projected habitat losses (Hoagland et al. 2011; McLaughlin and Zavaleta 2012). For example, modeling by McLaughlin and Zavaleta (2012) shows that valley oak may exhibit clustering around local microrefugia (e.g., water bodies) in response to increasingly warm and xeric conditions, and that sapling distribution may be more limited than adult distribution.

Adaptive Capacity

The overall adaptive capacity of oak woodland habitats was evaluated to be moderate by habitat experts.[19]

Habitat extent, integrity, continuity and landscape permeability
Habitat experts evaluated oak woodland habitats to have a moderate geographic extent (i.e., habitat occurs across the study region),[20] low-moderate integrity (i.e., habitat is partially degraded),[21] and feature moderate continuity (i.e., habitat patches with some connectivity between them).[22] Habitat experts identified land-use conversion and agriculture as barriers to habitat continuity and dispersal for this ecosystem type.[23]

Oak woodlands occupy roughly 10 million acres in California (Steinberg 2002). A majority of oak woodlands in California exist on private lands (Davis et al. 1998); varied land-use practices as a result of private ownership, as well as land-use conversion, have contributed to oak woodland habitat alteration and fragmentation (Howard 1992). These changes affect future oak habitat resilience and movement in the face of climate change, particularly since climatic restrictions (e.g., moisture, temperature) limit oak expansion (e.g., to inland areas). Some oak woodlands have also experienced extensive alteration through the establishment of non-native grasses in the understory and mortality associated with the GSOB (Vulnerability Assessment Reviewers, pers. comm., 2015).

Resistance and recovery
Habitat experts evaluated oak woodland habitats to have moderate resistance to climate stressors and maladaptive human responses,[24] and moderate recovery potential.[25] Some species, including coast live oak and Engelmann oak, can recover from disturbance and different land-use practices, such as agriculture, but opportunities to do so are becoming increasingly scarce due to development demands (Vulnerability Assessment Reviewers, pers.

[19] Confidence: High
[20] Confidence: High
[21] Confidence: Moderate
[22] Confidence: Moderate
[23] Barriers presented are those ranked most critical by habitat experts. A full list of evaluated barriers can be found at the end of this document.
[24] Confidence: Moderate
[25] Confidence: Moderate

comm., 2015). It is likely that non-climate stressors (e.g., development, herbivory) will interact with climate and climate-driven changes to affect oak woodland regeneration and recovery potential (Conlisk et al. 2012; Hayes and Donnelly 2014; Principe 2002; Sork et al. 2010).

Oaks are resilient to many disturbances, and the ability to resprout and establish from seed likely helps maintain genetic diversity after disturbance (Montalvo et al. 1997; Plumb and McDonald 1981). Although resilient to fire and drought, oaks may be less resilient to shifts in the intensity and frequency of these events, and oak adaptation, migration, and dispersal is unlikely to keep pace with climate change (Conlisk et al. 2012; Sork et al. 2010). In addition, it is believed that oak regeneration is declining in California, although landscape-scale proof and/or causal mechanisms are not clear (Hoagland et al. 2011; Matzner et al. 2003; Tyler et al. 2006; Zavaleta et al. 2007). Oaks typically have high spatial and temporal recruitment variability (Conlisk et al. 2012; Garcia et al. 1991; Koenig et al. 1994, 1996, 1999; Principe 2002), and take 20-30 years to reach reproductive maturity (Giusti et al. 2005 cited in Hoagland et al. 2011). Long life spans, immobility of established individuals, variability in reproductive capacity, and limited acorn dispersal ability undermine the ability of oak woodlands to move or exhibit rapid genetic adaptation to changing conditions (Conlisk et al. 2012; McLaughlin and Zavaleta 2012; Sork et al. 2010).

Oak canopies are typically comprised of only one or two species (CWHR 2015a, 2015c, 2015d); loss of foundational oak species undermines the resistance and diversity of the entire habitat and can lead to conversion to other vegetation communities (Rice et al. 1993). However, genetic variability amongst different regional and local oak populations will likely affect overall adaptive capacity and resilience, leading to spatially variable oak woodland responses to climatic variability (Montalvo et al. 1997; Sork et al. 2010).

Habitat diversity

Habitat experts evaluated oak woodland habitats to have moderate physical and topographical diversity,[26] moderate component species diversity,[27] and moderate functional group diversity.[28] Four CWHR oak woodland types exist in southern California: coastal oak woodland, montane hardwood, blue oak woodland, and valley oak woodland (CWHR 2015a, 2015c, 2015d). From Sonoma County south, coastal oak associations dominate (Holland 1988). Blue oak and valley oak woodlands, though dominant elsewhere in California (Gaman and Firman 2006), reach the southern end of their distribution in the southern California study region (i.e., near the Tejon Ranch; Hoagland et al. 2011).

Oak woodlands harbor high endemism, including species endemic to California (e.g., valley oak, blue oak) and specifically to southern California (e.g., Engelmann oak; Plumb and McDonald 1981). Oak woodlands also provide critical habitat for a variety of wildlife species (CDFWS 2015a, 2015b, 2015c, 2015d; Howard 1992; Tietje et al. 2005; Verner 1987). Oak species are

[26] Confidence: High
[27] Confidence: Moderate
[28] Confidence: Moderate

keystone; loss of these individuals would eliminate or cause severe changes in oak woodland habitat, affecting a variety of plant and animal species (Hayes and Donnelly 2014; Los Angeles County 2011; Rice et al. 1993) and ecosystem service provisioning (Pavlik et al. 1991 cited in Zavaleta et al. 2007).

Coastal oak woodland

Coastal oak woodland ecosystems are characterized by coast live oak, Engelmann oak, interior live oak, and California walnut (*Juglans californica*) (CWHR 2015a). Coast live oaks dominate a majority of southern oak woodlands (Bartolome 1987), with other species occurring as co-dominants in the canopy (CWHR 2015a). Coast live oak can persist on a variety of soil types, causing coastal oak woodland assemblages to be common among mesic foothills spanning the entire length of coastal California and into Baja California (Holland 1988). Interior live oak is more common on rocky outcrops at higher elevations, while California walnut can be locally dominant in Santa Barbara and Orange Counties (CWHR 2015a). Coastal oak woodlands can occur at elevations from near sea level on the immediate coast to 1,525 m (5,003 ft) further inland (CWHR 2015a; Holland 1988).

Montane hardwood

Montane hardwood oak ecosystems are characterized by canyon live oak, California black oak, and a variety of coniferous and other oak associates (CWHR 2015b). Montane hardwood habitat is widespread and occupies a range of slopes, in particular moderate to steep slopes. Soils are rocky, coarse, poorly developed, and well-drained, with depths ranging from shallow to deep. Montane hardwoods can persist in a wide range of physical settings, and are found throughout California, primarily on western mountain slopes at elevations between 100-2,745 m (328-9,005 ft; McDonald 1988).

Blue oak woodland

Blue oak woodland ecosystems are dominated by blue oak, which mixes with California juniper (*Juniperus californica*) in the southern Coast Range (CWHR 2015c). Blue oaks are the most common oak species in California and are well adapted to dry, hilly terrain (Gaman and Firman 2006; Ritter 1988a). Blue oak woodlands are found in the northern area of the study region (Hoagland et al. 2011), and become more abundant in central and northern California (Gaman and Firman 2006). This association can be found at elevations ranging from 76-915 m (249-3,001 ft; Ritter 1988a).

Valley oak woodland

Valley oak woodland ecosystems are dominated by valley oak, and include California walnut and California sycamore (*Platanus racemosa*) (CWHR 2015d). Valley oak woodlands typically occur below 610 m (2,001 ft) in deep soils of valleys, riparian habitats, and along foothills, although this woodland type has been reported at elevations up to 1,525 m (5,003 ft) in the Santa Lucia Mountains (Griffin 1976; Kueppers et al. 2005). Much former valley oak woodland habitat has already been degraded or eliminated and it is estimated that the current range is shrinking due to valley oak's relatively high reliance on groundwater and reduced tolerance to drought (Kueppers et al. 2005; McLaughlin and Zavaleta 2012).

Management potential

Habitat experts evaluated oak woodland habitats to be of high societal value.[29] Oak woodland habitats are valued for their recreational opportunities, scenic quality, tribal value, and wildlife habitat provisioning (Plumb and McDonald 1981; Vulnerability Assessment Reviewers, pers. comm., 2015). Oak woodland habitats provide a variety of ecosystem services, including: biodiversity, water supply/quality/sediment transport, grazing, recreation, carbon sequestration, nitrogen retention, air quality, and flood and erosion protection (Los Angeles County 2011; Vulnerability Assessment Reviewers, pers. comm., 2015).

Habitat experts identified that there is low-moderate potential for managing or alleviating climate impacts for oak woodland habitats.[30] Potential management options identified by habitat experts include: managing fire and fuels; managing non-native understory species to enhance recruitment; planting acorns and seedlings; and managing non-native pests (e.g. GSOB). The scientific literature also identifies the following potential management actions: fencing seedlings to enhance oak recruitment (Hoagland et al. 2011); utilizing prescribed fires to mitigate fuel accumulation and risk of severe wildfires (Howard 1992); maintaining groundwater levels and protecting potential microrefugia (Los Angeles County 2011; McLaughlin and Zavaleta 2012); maintaining biodiversity (Los Angeles County 2011); and practicing early identification and treatment of GSOB-infected areas to limit spread (Coleman et al. 2015; Haavik et al. 2015).

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Literature Cited

Bartolome, J. W. (1987). California annual grassland and oak savannah. *Rangelands, 9*(3), 122-125.

Bright, J. L., & Hervert, J. J. (2005). Adult and fawn mortality of Sonoran pronghorn. *Wildlife Society Bulletin*, *33*(1), 43–50.

California Wildlife Habitat Relationships System (CWHR). (2015a). Coastal oak woodland. Accessed Nov 15, 2015. Retrieved from https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=67344&inline=1

California Wildlife Habitat Relationships System (CWHR). (2015b). Montane hardwood. Accessed November 15, 2015. Retrieved from https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=67338&inline=1

California Wildlife Habitat Relationships System (CWHR). (2015c). Blue oak woodland. Accessed November 15, 2015. Retrieved from https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=67340&inline=1

[29] Confidence: High

[30] Confidence: Moderate

California Wildlife Habitat Relationships System (CWHR). (2015d). Valley oak woodland. Accessed November 15, 2015. Retrieved from https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=67342&inline=1

Callaway, R. M. (1990). Effects of soil water distribution on the lateral root development of three species of California oaks. *American Journal of Botany, 77*(11), 1469-1474.

Coleman, T. W., Grulke, N. E., Daly, M., Godinez, C., Schilling, S. L., Riggan, P. J., & Seybold, S. J. (2011). Coast live oak, Quercus agrifolia, susceptibility and response to goldspotted oak borer, Agrilus auroguttatus, injury in southern California. *Forest Ecology and Management, 261*(11), 1852-1865.

Coleman, T. W., Jones, M. I., Smith, S. L., Venette, R. C., Flint, M. L., & Seybold, S. J. (2015). Goldspotted oak borer. *Forest Insect & Disease Leaflet 183*. USDA Forest Service. Retrieved from http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3833276.pdf

Coleman, T. W., & Seybold, S. J. (2008). Previously unrecorded damage to oak, Quercus spp., in southern California by the goldspotted oak borer, Agrilus coxalis Waterhouse (Coleoptera: Buprestidae). *The Pan-Pacific Entomologist, 84*(4), 288-300.

Conlisk, E., Lawson, D., Syphard, A. D., Franklin, J., Flint, L., Flint, A., & Regan, H. M. (2012). The roles of dispersal, fecundity, and predation in the population persistence of an oak (Quercus engelmannii) under global change. *PloS ONE, 7*(5), e36391.

Danielsen, W. L., & Halvorson, K. C. (1991). Valley oak seedling growth associated with selected grass species. In R. B. Standiford (Ed.), *Proceedings of the symposium on oak woodlands and hardwood rangeland management; October 31-November 2, 1990: Davis, California* (pp. 9-13). (Gen. Tech. Rep. PSW-GTR-126). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://ftp.fs.fed.us/psw/publications/documents/psw_gtr126/psw_gtr126_01_danielsen.pdf

Davis, F. W., Stoms, D. M., Hollander, A. D., Thomas, K. A., Stine, P. A., Odion, D., . . . Graae, J. (1998). *The California gap analysis project: Final report*. Santa Barbara, CA: University of California, Santa Barbara. Retrieved from http://www.biogeog.ucsb.edu/projects/gap/gap_rep.html

Eskalen, A., Stouthamer, R., Lynch, S. C., Rugman-Jones, P. F., Twizeyimana, M., Gonzalez, A., & Thibault, T. (2013). Host range of Fusarium dieback and its ambrosia beetle (Coleoptera: Scolytinae) vector in southern California. *Plant Disease, 97*(7), 938-951.

Gaman, T., & Firman, J. (2006). *Oaks 2040: The status and future of oaks in California*. Oakland, CA: California Oak Foundation. Retrieved from http://new.californiaoaks.org/wp-content/uploads/2016/04/Oaks2040-Final.pdf

Garcia, S. L., Jensen, W. A., Weitkamp, W. H., & Tietje, W. D. (1991). Acorn yield during 1988 and 1989 on California's central coast. In R. B. Standiford (Ed.), *Proceedings of the symposium on oak woodlands and hardwood rangeland management; October 31-November 2, 1990: Davis, California* (pp. 161-163). (Gen. Tech. Rep. PSW-GTR-126). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://www.fs.fed.us/psw/publications/documents/psw_gtr126/psw_gtr126_02_garcia.pdf

Gogan, P. J. P., & Barrett, R. H. (1987). Comparative dynamics of introduced tule elk populations. *The Journal of Wildlife Management*, *51*(1), 20–27.

Gordon, D. R., & Rice, K. J. (2000). Competitive suppression of Quercus douglasii (Fagaceae) seedling emergence and growth. *American Journal of Botany, 87*(7), 986-994.

Griffin, D., & Anchukaitis, K. J. (2014). How unusual is the 2012–2014 California drought? *Geophysical Research Letters, 41*(24), 9017-9023.

Griffin, J. R. (1971). Oak regeneration in the upper Carmel Valley, California. *Ecology, 52*(5), 862-868.

Griffin, J. R. (1973). Xylem sap tension in three woodland oaks of central California. *Ecology, 54*(1), 152-159.

Griffin, J. R. (1976). Regeneration in Quercus lobata savannas, Santa Lucia Mountains, California. *American Midland Naturalist, 95*(2), 422-435.

Haavik, L. J., Flint, M. L., Coleman, T. W., Venette, R. C., & Seybold, S. J. (2015). Goldspotted oak borer effects on tree health and colonization patterns at six newly-established sites. *Agricultural and Forest Entomology, 17*(2), 146-157.

Hall, L. M., George, M. R., McCreary, D. D., & Adams, T. E. (1992). Effects of cattle grazing on blue oak seedling damage and survival. *Journal of Range Management, 45*(5), 503-506.

Hauptfeld, R. S. and Kershner, J. M. (2014). Sierra Nevada ecosystem vulnerability assessment briefing: Oak woodlands. Version 1.0. Bainbridge Island, WA: EcoAdapt. Retrieved from http://ecoadapt.org/data/documents/SierraNevada_OakWoodlands_VABriefing_23Oct2014.pdf

Hayes, J. J., & Donnelly, S. (2014). A resilience-based approach to the conservation of valley oak in a southern California landscape. *Land, 3*(3), 834-849.

Hoagland, S., Krieger, A., Moy, S., & Shepard, A. (2011). *Ecology and management of oak woodlands on Tejon Ranch: Recommendations for conserving a valuable California ecosystem* (Master of Environmental Science and Management). Santa Barbara, CA: University of California, Santa Barbara. Retrieved from http://www.bren.ucsb.edu/research/documents/tejonoaks_report.pdf

Holland, V.L. (1988). Coastal oak woodland. In K. E. Mayer and W. F. Laudenslayer Jr. (Eds.). *A guide to wildlife habitats of California*. Sacramento, CA: State of California, Resources Agency, Department of Fish and Game.

Howard, J. L. (1992). Quercus lobata. *Fire Effects Information System [Online].* Retrieved from http://www.fs.fed.us/database/feis/plants/tree/quelob/all.html

Jimerson, T. M., & Carothers, S. K. (2002). Northwest California oak woodlands: Environment, species composition, and ecological status. In R. B. Standiford (Ed.), *Proceedings of the fifth symposium on oak woodlands: Oaks in California's challenging landscape* (pp. 705-717). (Gen. Tech. Rep. PSW-GTR-184). Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://www.treesearch.fs.fed.us/pubs/26167

Koenig, W. D., Knops, J. M., Carmen, W. J., & Stanback, M. T. (1999). Spatial dynamics in the absence of dispersal: Acorn production by oaks in central coastal California. *Ecography, 22*(5), 499-506.

Koenig, W. D., Knops, J. M., Carmen, W. J., Stanback, M. T., & Mumme, R. L. (1996). Acorn production by oaks in central coastal California: Influence of weather at three levels. *Canadian Journal of Forest Research, 26*(9), 1677-1683.

Koenig, W. D., Mumme, R. L., Carmen, W. J., & Stanback, M. T. (1994). Acorn production by oaks in central coastal California: Variation within and among years. *Ecology, 75*(1), 99-109.

Kueppers, L. M., Snyder, M. A., Sloan, L. C., Zavaleta, E. S., & Fulfrost, B. (2005). Modeled regional climate change and California endemic oak ranges. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(45), 16281-16286.

Lathrop, E. W., & Osborne, C. D. (1991). Influence of fire on oak seedlings and saplings in a southern oak woodland on the Santa Rosa Plateau Preserve, Riverside County, California. In R. B. Standiford (Ed.), *Proceedings of the symposium on oak woodlands and hardwood rangeland management; October 31-November 2, 1990: Davis, California* (pp. 366-370). (Gen. Tech. Rep. PSW-GTR-126). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://www.treesearch.fs.fed.us/pubs/28459

Los Angeles County Oak Woodlands Habitat Conservation Strategic Alliance (Los Angeles County). (2011). *Los Angeles County Oak Woodlands Conservation Management Plan*. Los Angeles County Oak Woodlands Habitat Conservation Strategic Alliance. Retrieved from http://planning.lacounty.gov/oakwoodlands/documents

Matzner, S. L., Rice, K. J., & Richards, J. H. (2003). Patterns of stomatal conductance among blue oak (Quercus douglasii) size classes and populations: Implications for seedling establishment. *Tree Physiology, 23*(11), 777-784.

McCreary, D.D. (2004). Fire in California's oak woodlands. Browns Valley, CA: University of California Cooperative Extension. Retrieved from http://ucanr.edu/sites/oak_range/files/59574.pdf

McDonald, P. M. (1990). Quercus kelloggii Newb. California black oak. In R. M. Burns & B. H. Honkala, (tech. coord.), *Silvics of North America, Vol. 2, Hardwoods. Agricultural Handbook 654.* (pp. 661-671). Washington, D.C.: U.S. Department of Agriculture.

McDonald, P.M. (1988). Montane hardwood. In K. E. Mayer and W. F. Laudenslayer Jr. (Eds.). *A guide to wildlife habitats of California*. Sacramento, CA: State of California, Resources Agency, Department of Fish and Game.

McDonald, P. M., & Tappeiner, J. C. (1996). Silviculture-ecology of forest-zone hardwoods in the Sierra Nevada. In *Sierra Nevada ecosystem project: Final report to Congress, Volume 3: Assessments and scientific basis for management options* (pp. 621-636). Davis, CA: University of California: Centers for Water and Wildlife Resources. Retrieved from http://pubs.usgs.gov/dds/dds-43/VOL_III/VIII_C14.PDF

McLaughlin, B. C., and Zavaleta, E. S. (2012). Predicting species responses to climate change: Demography and climate microrefugia in California valley oak (Quercus lobata). *Global Change Biology*, *18*(7), 2301-2312.

Meentemeyer, R., 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*(1), 195-214.

Montalvo, A., Conard, S., Conkle, M., & Hodgskiss, P. (1997). Population structure, genetic diversity, and clone formation in Quercus chrysolepis (Fagaceae). *American Journal of Botany, 84*(11), 1553-1553.

Moore, J. E., & Swihart, R. K. (2007). Importance of fragmentation-tolerant species as seed dispersers in disturbed landscapes. *Oecologia*, *151*(4), 663-674.

Muick, P. C. (1991). Effects of shade on blue oak and coast live oak regeneration in California annual grasslands. In R. B. Standiford (Ed.), *Proceedings of the symposium on oak woodlands and hardwood rangeland management; October 31-November 2, 1990; Davis, California* (pp. 21-24). (Gen. Tech. Rep. PSW-GTR-126). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://www.fs.fed.us/psw/publications/documents/psw_gtr126/psw_gtr126_01_muick.pdf

Paysen, T. E., & Narog, M. G. (1993). Tree mortality 6 years after burning a thinned Quercus chrysolepis stand. *Canadian Journal of Forest Research, 23*(10), 2236-2241.

Plumb, T. R. (1982). Factors affecting germination of southern California oaks. In C. E. Conrad & W. C. Oechel (Eds.), *Proceedings of the symposium on dynamics and management of Mediterranean-type ecosystems; June 22-26, 1991; San Diego, California* (pp. 625). (Gen. Tech. Rep. GTR-PWS-58). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station.

Plumb, T. R., & De Lasaux, M. D. (1997). An evaluation of coast live oak regeneration techniques. In N. H. Pillsbury, J. Verner, & W. D. Tietje (tech. coord.), *Proceedings of the symposium on oak woodlands: Ecology, management, and urban interface issues; March 19–22, 1996; San Luis Obispo, California.* (pp. 231-242). (Gen. Tech. Rep. PSW-GTR-160). Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://www.fs.fed.us/psw/publications/documents/psw_gtr160/psw_gtr160_04b_plumb.pdf

Plumb, T. R., & Gomez, A. P. (1983). *Five southern California oaks: identification and postfire management*. (Gen. Tech. Rep. PSW-GTR-71). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. Retrieved from http://www.fs.fed.us/psw/publications/documents/psw_gtr071/psw_gtr071a.pdf

Plumb, T. R., & Hannah, B. (1991). Artificial regeneration of blue and coast live oaks in the central coast. In R. B. Standiford (Ed.), *Proceedings of the symposium on oak woodlands and hardwood rangeland management; October 31-November 2, 1990; Davis, California* (pp. 74-80). (Gen. Tech. Rep. PSW-GTR-126). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://www.treesearch.fs.fed.us/pubs/28401

Plumb, T. R., & Kraus, K. (1991). Oak woodland artificial regeneration — correlating soil moisture to seedling survival. In R. B. Standiford (Ed.), *Proceedings of the symposium on oak woodlands and hardwood rangeland management; October 31-November 2, 1990; Davis, California.* (pp. 91-95). (Gen. Tech. Rep. PSW-GTR-126). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://www.treesearch.fs.fed.us/pubs/28404

Plumb, T. R., & McDonald, P. M. (1981). *Oak management in California*. (Gen. Tech. Rep. GTR-PSW-54). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. Retrieved from http://www.fs.fed.us/psw/publications/documents/psw_gtr054/psw_gtr054.pdf

Principe, Z. (2015). Influence of fire on Engelmann oak survival – patterns following prescribed fires and wildfires. In R. B. Standiford & K. Purcell (Eds.), *Proceedings of the seventh California oak symposium: Managing oak woodlands in a dynamic world* (pp. 175–185). (Gen. Tech. Rep. PSW-GTR-251). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://www.treesearch.fs.fed.us/pubs/49983

Principe, Z.A. (2002). *Factors affecting Engelmann oak (Quercus engelmannii) regeneration.* (Master of Science). San Diego, CA: San Diego State University.

Principe, Z. A., MacKenzie, J. B., Cohen, B., Randall, J. M., Tippets, W., Smith, T., & Morrison, S. A. (2013). *50-year climate scenarios and plant species distribution forecasts for setting conservation priorities in Southwestern California*. San Francisco, CA: The Nature Conservancy of California. Retrieved from http://scienceforconservation.org/dl/SW_CA_Climate_Report_v1_Oct_2013.pdf

Rice, K. J., Gordon, D. R., Hardison, J. L., & Welker, J. M. (1993). Phenotypic variation in seedlings of a "keystone" tree species (Quercus douglasii): The interactive effects of acorn source and competitive environment. *Oecologia*, *96*(4), 537–547. http://doi.org/10.1007/BF00320511

Ripple, W. J., & Beschta, R. L. (2008). Trophic cascades involving cougar, mule deer, and black oaks in Yosemite National Park. *Biological Conservation*, *141*(5), 1249-1256.

Ritter, L. V. (1988a). Blue oak woodland. In K. E. Mayer and W. F. Laudenslayer Jr. (Eds.). *A guide to wildlife habitats of California*. Sacramento, CA: State of California, Resources Agency, Department of Fish and Game.

Ritter, L. V. (1988b). Valley oak woodland. In K. E. Mayer and W. F. Laudenslayer Jr. (Eds.). *A guide to wildlife habitats of California*. Sacramento, CA: State of California, Resources Agency, Department of Fish and Game.

Rizzo, D., Garbelotto, M., Davidson, J., Slaughter, G., & Koike, S. (2002). Phytophthora ramorum as the cause of extensive mortality of Quercus spp. and Lithocarpus densiflorus in California. *Plant Disease, 86*(3), 205-214.

Snow, G. E. (1991). Germination characteristics of Engelmann Oak and Coast Live Oak from the Santa Rosa Plateau, Riverside County, California. In R. B. Standiford (Ed.), *Proceedings of the symposium on oak woodlands and hardwood rangeland management; October 31-November 2, 1990; Davis, California* (pp. 360-365). (Gen. Tech. Rep. PSW-GTR-126). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://www.treesearch.fs.fed.us/pubs/28458

Sork, V. L., Davis, F. W., Smouse, P. E., Apsit, V. J., Dyer, R. J., Fernandez-M, J., & Kuhn, B. (2002). Pollen movement in declining populations of California Valley oak, Quercus lobata: Where have all the fathers gone? *Molecular Ecology, 11*(9), 1657-1668.

Sork, V. L., Davis, F. W., Westfall, R., Flint, A., Ikegami, M., Wang, H., & Grivet, D. (2010). Gene movement and genetic association with regional climate gradients in California valley oak (Quercus lobata Née) in the face of climate change. *Molecular Ecology, 19*(17), 3806-3823.

Steinberg, P. D. (2002). Quercus agrifolia. *Fire Effects Information System, [Online].* Retrieved from http://www.fs.fed.us/database/feis/plants/tree/queagr/all.html#27

Swiecki, T. J., & Bernhardt, E. (1998). Understanding blue oak regeneration. *Fremontia, 26*(1), 19-26.

Syphard, A. D., Clarke, K. C., & Franklin, J. (2007). Simulating fire frequency and urban growth in southern California coastal shrublands, USA. *Landscape Ecology, 22*(3), 431-445.

Tietje, W., Purcell, K., & Drill, S. (2005). Oak woodlands as wildlife habitat. In G. A. Guisti, D. D. McCreary, & R. B. Standiford (Eds.), *A planner's guide for oak woodlands* (2nd ed.): University of California, Division of Agriculture and Natural Resources, Publication 3491.

Tyler, C. M., Davis, F. W., & Mahall, B. E. (2008). The relative importance of factors affecting age-specific seedling survival of two co-occurring oak species in southern California. *Forest Ecology and Management, 255*(7), 3063-3074.

Tyler, C. M., Kuhn, B., & Davis, F. W. (2006). Demography and recruitment limitations of three oak species in California. *The Quarterly Review of Biology*, *81*(2), 127-152.

University of California Cooperative Extension. (2015). Goldspotted oak borer: Distribution. Retrieved from http://ucanr.edu/sites/gsobinfo/About_Goldspotted_Oak_Borer_930/Location/

U.S. Fish and Wildlife Service. (1998). *Recovery Plan for Upland Species of the San Joaquin Valley, California*. Portland, OR: U.S. Fish and Wildlife Service. Retrieved from http://ecos.fws.gov/docs/recovery_plans/1998/980930a.pdf

Verner, J. (1987). The importance of hardwood habitats for wildlife in California. In T.R. Plumb & N.H. Pillsbury (Eds.), *Proceedings of the symposium on multiple-use management of California's hardwood resources; November 12-14, 1986; San Luis Obispo, California* (pp. 162). (Gen. Tech. Rep. PSW-100). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from http://www.fs.fed.us/psw/publications/documents/psw_gtr100/psw_gtr100_004.pdf

Waddell, K. L., & Barrett, T. M. (2005). *Oak woodlands and other hardwood forests of California, 1990s*. (Resource Bulletin PNW-RB-245). Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station. Retrieved from http://www.fs.fed.us/pnw/pubs/pnw_rb245.pdf

Zavaleta, E. S., Hulvey, K. B., & Fulfrost, B. (2007). Regional patterns of recruitment success and failure in two endemic California oaks. *Diversity and Distributions, 13*(6), 735-745.

Oak Woodland Habitats – Overview of Vulnerability Component Evaluations

Overall Vulnerability Ranking:[1] **2 Low-Moderate** **Overall Confidence:**[2] **3 High**

SENSITIVITY

Sensitivity Factor[3]	Sensitivity Evaluation[4]	Confidence[4]
Sensitivities to Climate & Climate-Driven Factors	**Overall: 2 Low-Moderate**	**Overall: 3 High**
• *Precipitation*	• 4 Moderate-High	• 3 High
• *Soil moisture*	• 4 Moderate-High	• 2 Moderate
• *Air temperature*	• 2 Low-Moderate	• 3 High
• Extreme events: drought[5]	• 5 High	• 3 High
• Extreme events: high temperature[5]	• 3 Moderate	• 3 High
• Low stream flows[6]	• 2 Low-Moderate	• 3 High
• Snowpack depth[6]	• 1 Low	• 3 High
• Timing of snowmelt & runoff[6]	• 1 Low	• 3 High
• Extreme events: low temperature[6]	• 1 Low	• 3 High
• Other (elevated carbon dioxide)[7]	• 3 Moderate	• 3 High
• High lentic/lotic temperature[7]	• 1 Low	• 1 Low
Disturbance Regimes	**Overall: 2 Low-Moderate**	**Overall: 1 Low**
• Wildfire[5]	• 3 Moderate	• 2 Moderate
• Disease[5]	• 3 Moderate	• 1 Low
• Insects[6]	• 3 Moderate	• 1 Low
• Flooding[7]	• 1 Low	• 1 Low
• Wind[7]	• 1 Low	• 1 Low
Non-Climate Stressors – Degree Stressor Affects Sensitivity	**Overall: 3 Moderate**	**Overall: 2 Moderate**
• *Invasive & other problematic species*	• 4 Moderate-High	• 2 Moderate
• *Land use conversion*	• 3 Moderate	• 2 Moderate
• *Livestock grazing*	• 2 Low-Moderate	• 2 Moderate
• Agriculture & aquaculture[7]	• 4 Moderate-High	• 3 High
• Recreation[7]	• 2 Low-Moderate	• 2 Moderate
• Fire suppression practices[7]	• 1 Low	• 2 Moderate

[1] Overall vulnerability is calculated according to the following formula: Vulnerability = Sensitivity * (0.5*Exposure) - Adaptive Capacity.
[2] Overall confidence is an average of the overall averaged confidences for sensitivity, exposure, and adaptive capacity.
[3] Factors with expert consensus are *italicized*; all other factors indicate the percentage of experts who identified that factor as important to consider for the habitat.
[4] Scores presented reflect an average of all scores given by habitat experts for a given factor.
[5] Identified by 75% of habitat experts.
[6] Identified by 50% of habitat experts.
[7] Identified by 25% of habitat experts.

Sensitivity Factor[3]	Sensitivity Evaluation[4]	Confidence[4]
Non-Climate Stressors – Current Exposure to Stressor • *Invasive & other problematic species* • *Land use conversion* • *Livestock grazing* • Agriculture & aquaculture[7] • Recreation[7] • Fire suppression practices[7]	**Overall: 3 Moderate** • 4 Moderate-High • 3 Moderate • 1 Low • 4 Moderate-High • 4 Moderate-High • 3 Moderate	**Overall: 3 High** • 2 Moderate • 2 Moderate • 2 Moderate • 3 High • 2 Moderate • 3 High
Other Sensitivities: none identified	N/A	N/A

Overall Averaged Ranking (Sensitivity):[8] 2 Low-Moderate

Overall Averaged Confidence (Sensitivity):[9] 2 Moderate

EXPOSURE

Exposure Factor[3]	Exposure Evaluation[4]	Confidence[4]
Future Climate Exposure Factors • *Decreased soil moisture* • *Increased air temperature* • *Extreme events: high temperatures* • *Changes in precipitation* • *Increased wildfire* • Extreme events: increased drought[6] • Decreased snowpack[6] • Earlier snowmelt & runoff[7] • Increased lentic/lotic temperatures[7] • Altered stream flows[7] • Extreme events: high flows & runoff[7] • Extreme events: low temperatures[7]	**Overall: 2 Low-Moderate** • 5 High • 4 Moderate-High • 4 Moderate-High • 3 Moderate • 3 Moderate • 4 Moderate-High • 2 Low-Moderate • 1 Low • 1 Low • 1 Low • 1 Low • 1 Low	**Overall: 3 High** • 2 Moderate • 2 Moderate • 2 Moderate • 2 Moderate • 2 Moderate • 2 Moderate • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High

Overall Averaged Ranking (Exposure):[8] 2 Low-Moderate

Overall Averaged Confidence (Exposure):[9] 3 High

ADAPTIVE CAPACITY

Adaptive Capacity Factor	Adaptive Capacity Evaluation[4]	Confidence[4]
Habitat Extent, Integrity & Continuity • Geographic Extent • Structural & Functional Integrity	**Overall: 3 Moderate** • 3 Moderate (Occurs across study region) • 2 Low-Moderate (Partially degraded)	**Overall: 3 High** • 3 High • 2 Moderate

[8] Overall averaged ranking is an average of the sensitivity, adaptive capacity, or exposure evaluation columns above.

[9] Overall averaged confidence is an average of the confidence column for sensitivity, adaptive capacity, or exposure.

Adaptive Capacity Factor	Adaptive Capacity Evaluation[4]	Confidence[4]
• Habitat Continuity	• 3 Moderate (Patches with connectivity between them)	• 2 Moderate
Landscape Permeability[3] Key barriers: • *Land use conversion* • *Agriculture* • Transportation corridors[6] • Geologic features[6] • Grazing[7] • Timber harvest & clear cuts[7] • Energy production & mining[7] • Dams & water diversions[7]	**Overall: 4 Moderate-High** Impact on landscape permeability: • High • Moderate • Moderate-High • Low-Moderate • Low-Moderate • Low • Low • Low	**Overall: 3 High** • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High • 3 High
Habitat Resistance & Recovery • Resistance • Recovery	**Overall: 3 Moderate** • 3 Moderate • 3 Moderate	**Overall: 2 Moderate** • 2 Moderate • 2 Moderate
Habitat Diversity • Physical/Topographical Diversity • Component Species Diversity • Functional Group Diversity	**Overall: 3 Moderate** • 3 Moderate • 3 Moderate • 3 Moderate	**Overall: 2 Moderate** • 3 High • 2 Moderate • 2 Moderate
Management Potential • Habitat Value • Likelihood of Managing or Alleviating Climate Impacts	**Overall: 4 Moderate-High** • 5 High • 2 Low-Moderate	**Overall: 3 High** • 3 High • 2 Moderate
Other Adaptive Capacities: none identified	N/A	N/A

Overall Averaged Ranking (Adaptive Capacity):[8] 3 Moderate

Overall Averaged Confidence (Adaptive Capacity):[9] 3 High