



## Sugar Pine (*Pinus lambertiana*)

### Northern California Climate Change Vulnerability Assessment Synthesis

**An Important Note About this Document:** This document represents an initial evaluation of vulnerability for sugar pine in northern California based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by regional experts, relevant references from the scientific literature, and peer-review comments and revisions (see end of document for a glossary of terms and brief overview of study methods). 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.

Peer reviewers for this document included Anonymous (University of California, Berkeley), Arnaldo Ferreira (U.S. Forest Service), Frank Lake (U.S. Forest Service), Patricia Maloney (University of California, Davis), and Malcolm North (U.S. Forest Service and University of California, Davis). Vulnerability scores were provided by Eureka workshop participants.

---

## Table of Contents

<b>Species Description</b> .....	<b>1</b>
<b>Executive Summary</b> .....	<b>3</b>
<b>Sensitivity and Exposure</b> .....	<b>4</b>
<i>Sensitivity and future exposure to climate and climate-driven factors</i> .....	5
<i>Sensitivity and future exposure to changes in natural disturbance regimes</i> .....	9
<i>Dependency on habitat and/or other species</i> .....	15
<i>Sensitivity and current exposure to non-climate stressors</i> .....	15
<b>Adaptive Capacity</b> .....	<b>17</b>
<i>Species extent, status, connectivity, and dispersal ability</i> .....	17
<i>Intraspecific/life history diversity</i> .....	17
<i>Resistance and recovery</i> .....	18
<i>Management potential</i> .....	19
Public and societal value .....	19
Management capacity and ability to alleviate impacts .....	19
Ecosystem services .....	21
<b>Recommended Citation</b> .....	<b>21</b>
<b>Literature Cited</b> .....	<b>21</b>
<b>Vulnerability Assessment Methods and Application</b> .....	<b>31</b>

---

## Species Description

Sugar pine (*Pinus lambertiana*) is distributed from north-central Oregon down through California and far western Nevada, with isolated populations occurring as far south as Baja California in Mexico (Kinloch & Scheuner 1990). Within northern California, this species is found throughout the North Coast Range, Klamath Mountains, and the west slopes of the southern Cascades (Kinloch & Scheuner 1990) at elevations that range from 320 m (1,050 ft) to over

2,000 m (6,550 ft; Calflora 2019; Vuln. Assessment Reviewer, pers. comm., 2019). Sugar pine is the tallest and largest species in the genus, and can grow up to 74 m (241 ft) in height and 919 cm (362 in) in diameter (American Forests 2018), with trees potentially reaching over 500 years of age (Kinloch & Scheuner 1990).

Sugar pine is most commonly found as a component of mixed conifer forests, and usually occurs singly or in small groups rather than pure stands (Kinloch & Scheuner 1990). Sugar pine can be found across a wide range of site conditions ranging from mesic to xeric and on all aspects (Kinloch & Scheuner 1990; Habeck 1992; Bekker & Taylor 2001; Taylor & Skinner 2003; Skinner et al. 2009), though it is generally found on warmer exposures as elevation increases (Habeck 1992). Optimal growth appears to occur on more gentle terrain at middle elevations (Kinloch & Scheuner 1990). Sugar pine is often associated with Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), incense cedar (*Calocedrus decurrens*), Jeffrey pine (*P. jeffreyi*), white fir (*Abies concolor*), knobcone pine (*P. attenuata*), Port-Orford-cedar (*Chamaecyparis lawsoniana*), California black oak (*Quercus kelloggii*), tanoak (*Notholithocarpus densiflorus*), and Pacific madrone (*Arbutus menziesii*), as well as a diverse mix of other conifers and hardwoods found in lesser proportions depending on site conditions, topography, and disturbance history (Kinloch & Scheuner 1990; CNPS 2019). Understory shrubs frequently associated with sugar pine include *Ceanothus* spp., greenleaf manzanita (*Arctostaphylos patula*), bearclover (*Chamaebatia foliolosa*), bush chinquapin (*Chrysolepsis sempervirens*), serviceberry (*Amelanchier* spp.), salal (*Gaultheria shallon*), coast rhododendron (*Rhododendron californicum*), and *Ribes* spp. (Kinloch & Scheuner 1990; Vuln. Assessment Reviewer, pers. comm., 2019).

Sugar pines, including both standing live or dead (snag) trees, are highly valued by northwestern California tribes for subsistence, ceremonial, and spiritual uses, and some standing trees are spiritually-significant landscape markers (Driver 1939; Kroeber & Gifford 1949; Schenck & Gifford 1952; Lake 2013; Norgaard et al. 2016; Karuk Tribe 2019). Groves of sugar pine are managed by families for nuts, pitch, and roots (Schenck & Gifford 1952). Sugar pine nuts are collected in the late fall by gathering fallen cones or shaking them down from the tree. The cones are then heated under a fire, which allows the seeds to be more easily removed and eaten or stored (Schenck & Gifford 1952; Lake 2013), or passively dried until the cone scales open and nuts can be shaken out (F. Lake, pers. comm., 2019). Black pitch collected from sugar pine snags is highly valued, serving as a traditional form of currency. It is also utilized as medicine, adhesive, and in the ignition of cultural burns (Schenck & Gifford 1952; Norgaard et al. 2016; Karuk Tribe 2019). Finally, the roots are used to make waterproof baskets by some tribes (Schenck & Gifford 1952; Lake 2013). Sugar pines are considered particularly valuable when they occur within or near tanoak or black oak stands (Karuk DNR 2009; Norgaard et al. 2016).

## Executive Summary

The relative vulnerability of sugar pine in northern California was evaluated as moderate by regional experts due to moderate sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and moderate adaptive capacity.

Sugar Pine	Rank	Confidence
Sensitivity	Moderate	High
Future Exposure	Moderate-High	Moderate
Adaptive Capacity	Moderate	Moderate
<b>Vulnerability</b>	<b>Moderate</b>	<b>Moderate</b>

<b>Sensitivity &amp; Exposure Summary</b>	<p><u>Climate and climate-driven factors:</u></p> <ul style="list-style-type: none"> <li>• Climatic water deficit, soil moisture, drought, snowpack amount, timing of snowmelt and runoff, air temperature</li> </ul> <p><u>Disturbance regimes:</u></p> <ul style="list-style-type: none"> <li>• Disease (including white pine blister rust), wildfire, insects</li> </ul> <p><u>Non-climate stressors:</u></p> <ul style="list-style-type: none"> <li>• Fire exclusion (including suppression), timber harvest</li> </ul>
---	---

Sugar pine is particularly sensitive to climate stressors that alter water availability, including changes in soil moisture, drought, depth of snowpack, the timing of snowmelt and runoff, and air temperature. Moisture stress reduces seedling recruitment and tree vigor, increasing sugar pine mortality from drought, insect attack, disease, and other secondary stressors. Drier conditions also reduce the moisture level of potential wildfire fuels and increase the length of the fire season, while warmer temperatures will increase climate-driven outbreaks by bark beetles, which preferentially attack drought-stressed trees. The spread of white pine blister rust has contributed to population declines in many areas, particularly on moist sites and/or where alternate hosts (*Ribes* spp.) are abundant. This disease is likely to impact the future persistence of the species, particularly recruitment of seedlings and survivorship of younger trees.

Although sugar pines are resistant to low- and moderate- severity fire, altered wildfire regimes and more frequent and/or more severe insect outbreaks are likely to increase mortality in mature sugar pines with high ecological and cultural value. Fire exclusion has further predisposed sugar pines to these stressors by increasing the density of other trees (competitors), increasing water stress and reducing tree vigor. Fuel loading associated with fire exclusion has also increased surface and ladder fuels around sugar pines, contributing to increases in fire intensity and tree mortality. Finally, the loss of large trees due to historical timber harvest, followed by enhanced competition for soil moisture, light, and nutrients fire exclusion contributes to increased tree density, has reduced sugar pine regeneration and further increased the vulnerability of this species to climate changes.

<b>Adaptive Capacity Summary</b>	<p><u>Factors that enhance adaptive capacity:</u></p> <ul style="list-style-type: none"> <li>+ High genetic and phenotypic diversity support local adaptation to stress</li> <li>+ Highly valued by northern California tribes that advocate for increased societal support</li> <li>+ Identification and artificial regeneration of rust-resistant trees may enhance seedling survival</li> </ul> <p><u>Factors that undermine adaptive capacity:</u></p> <ul style="list-style-type: none"> <li>– Many populations have declined due to a combination of disease, fire exclusion, and other stressors</li> <li>– Low resistance to drought, insect attack, and other disturbances in dense stands</li> </ul>
----------------------------------	--

Although sugar pine has a broad latitudinal distribution and tolerates a wide range of environmental conditions, many populations across the state have declined due to a combination of disease, fire exclusion, and other stressors. Historically high genetic and phenotypic diversity has allowed the development of local adaptation to drought and disease in some areas. However, genetic diversity may be impacted in some locations as populations decline, possibly limiting the potential for adaptation to future climate changes. Resilience to future changes may be particularly limited on sites where resource competition in dense stands has reduced tree vigor. Sugar pine is highly valued by tribal communities in the region, and the scientific literature suggests several management strategies that may reduce the vulnerability of sugar pine to white pine blister rust and changing climate stressors. These include reducing forest density to limit competition, reintroducing frequent low-intensity fire to enhance regeneration and maintain forest structure, and identifying and planting rust-resistant stock.

## Sensitivity and Exposure

Sugar pine was evaluated by regional experts as having moderate overall sensitivity (high confidence in evaluation) and moderate-high overall future exposure (moderate confidence) to climate and climate-driven factors, changes in disturbance regimes, and non-climate stressors.

Range shifts for sugar pine may occur in response to changing climate conditions, including warmer temperatures and altered precipitation patterns (Monleon & Lintz 2015; Serra-Diaz et al. 2016). Some studies have observed shifts in average sugar pine regeneration towards lower elevations (Monleon & Lintz 2015; Serra-Diaz et al. 2016), which corresponds to a slight increase in mean annual temperature (Monleon & Lintz 2015). Little to no latitudinal shifts have been observed to date (Monleon & Lintz 2015; Serra-Diaz et al. 2016). Overall, patterns of seedling distribution suggest future range contractions may occur (Serra-Diaz et al. 2016), although a study of 62 conifer and hardwood species in the western U.S. found that sugar pine is projected to have increased seedling recruitment across its range (Dobrowski et al. 2015). It is important to note, however, that projections of species distribution typically do not incorporate more complex, interacting

Potential Changes in Species Distribution
<ul style="list-style-type: none"> <li>• Shifts towards warmer temperatures at lower elevations</li> <li>• Overall range contractions are likely, although increased seedling recruitment has also been projected</li> </ul>
<p>Source(s): Monleon &amp; Lintz 2015; Dobrowski et al. 2015; Serra-Diaz et al. 2016</p>

factors, including disturbances (e.g., disease, wildfire), seed dispersal, and phenotypic variation, among many others.

### **Sensitivity and future exposure to climate and climate-driven factors**

Regional experts evaluated sugar pine as having moderate sensitivity to climate and climate-driven factors (high confidence in evaluation), with an overall moderate-high future exposure to these factors within the study region (moderate confidence). Key climatic factors that affect sugar pine include climatic water deficit, soil moisture, drought, snowpack amount, timing of snowmelt and runoff, and air temperature.<sup>1</sup>

#### Climatic water deficit, soil moisture, and drought

Soil moisture and climatic water deficit are important drivers of sugar pine distribution (Bekker & Taylor 2001; Taylor & Skinner 2003; Lutz et al. 2010), although this species can be found across a relatively wide moisture gradient ranging from dry lower-elevation mixed conifer forests into moist upper-elevation forests dominated by white fir (Bekker & Taylor 2001; Taylor & Skinner 2003). Climatic water deficit (CWD) is a “plant-relevant” measurement of moisture stress that takes into account the interaction between water (precipitation) and energy (temperature; Stephenson 1998).<sup>2</sup> The balance between water supply and demand in California shifts over the course of the year, with CWD increasing as soil moisture from snowpack and winter rains is depleted and evapotranspiration increases in warmer months (Stephenson 1998). However, factors such as soil depth and type (granitic, volcanic, ultramafic, etc.) significantly affect the water-holding capacity of soil, and topographic features such as north-facing slopes can mediate CWD at a site-level scale (Dobrowski 2011; Flint et al. 2013; Reilly et al. 2018).<sup>3</sup>

Soil moisture and corresponding water stress impact sugar pine recruitment (Gray et al. 2005; North et al. 2005; Zald et al. 2008; Legras et al. 2010), growth (Angell et al. 2014), mortality (Pharis 1966; van Mantgem & Stephenson 2007; van Mantgem et al. 2009; Lutz et al. 2010; Fettig et al. 2019), and response to bark beetle attack (Maloney et al., unpublished data). Sugar pine seedlings require abundant soil moisture for growth and survival (North et al. 2005), and several studies have found increased post-fire sugar pine establishment during wet years (North et al. 2005; Young & Latimer 2017). Seedlings rapidly develop a long taproot to help them avoid summer drought (Pharis 1966; Habeck 1992), and local genetic adaptation to

---

<sup>1</sup> Climate and climate-driven factors presented are those ranked as having a moderate or higher impact on this species; additional climate and climate-driven factors that may influence the species to a lesser degree include storms.

<sup>2</sup> CWD, which is calculated as potential evapotranspiration (PET) minus actual evapotranspiration (AET), measures the degree to which the impact of local atmospheric conditions (particularly air temperature and relative humidity) on plants and soil exceeds available moisture (Stephenson 1998). Due to increased evaporative demand as temperatures rise, even areas where precipitation may increase are expected to see a rise in climatic water deficit (CWD) under future climate conditions (Thorne et al. 2015; Micheli et al. 2018).

<sup>3</sup> Soil moisture is based on CWD (i.e., balance between water supply and water demand) and soil properties, including porosity, depth, and underlying geology. These properties determine the soil water-holding capacity (i.e., how much moisture can be stored and used for plant evapotranspiration; Stephenson 1998; Flint et al. 2013).

drought has been observed among sugar pine populations in California (Vangestel et al. 2016) and at landscape scales in the Lake Tahoe Basin (Eckert et al. 2015; Maloney et al. 2019).

Reduced vigor due to water stress increases sugar pine vulnerability to severe drought, insects, and disease, particularly on dry sites and in dense stands where competition for soil moisture is high (van Mantgem & Stephenson 2007; van Mantgem et al. 2009; Allen et al. 2010; Kaiser et al. 2013; Das et al. 2016; Young et al. 2017; Fettig et al. 2019). For instance, high CWD is associated with more limited carbon allocation to resin ducts, impacting the effectiveness of tree defense systems that protect against bark beetle attack (Slack et al. 2017). Multiple studies have found higher rates of both background mortality and large-scale dieback in sugar pine and other mixed conifer forest species on drier sites and those near the limits of their range (van Mantgem & Stephenson 2007; van Mantgem et al. 2009; Lutz et al. 2010; Young et al. 2017). Large-scale mortality events can occur during periods of severe drought, when dense stands are vulnerable to attack by mountain pine beetles (*Dendroctonus ponderosae*; Fettig et al. 2019). However, a recent retrospective analysis of water-use efficiency in beetle-killed and surviving trees from the 2012–2016 drought found that surviving trees were better-adapted to dry conditions, allowing them to survive both the drought and mountain pine beetle attack (Maloney et al., manuscript in prep). By contrast, beetle-killed sugar pines utilized water less efficiently, making them more susceptible to drought and subsequent beetle attack.

<b>Regional Climatic Water Deficit (CWD), Soil Moisture, &amp; Drought Trends<sup>4</sup></b>	
<p><i>Historical &amp; current trends:</i></p> <ul style="list-style-type: none"> <li>• 1.1 cm (0.4 in) decrease to 0.4 cm (0.2 in) increase in average annual CWD between 1900 and 2009 for the Northwestern California and Southern Cascade ecoregions (Rapacciuolo et al. 2014)</li> <li>• Drought years have occurred twice as often over the last two decades compared to the previous century (Diffenbaugh et al. 2015)</li> <li>• 2012–2014 drought set records for lowest precipitation, highest temperatures, and most extreme drought indicators on record (Griffin &amp; Anchukaitis 2014; Diffenbaugh et al. 2015)</li> <li>• No trends available for soil moisture</li> </ul>	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> <li>• Increases in average annual CWD by 2100 (compared to 1951–1980; Flint et al. 2013; Flint &amp; Flint 2014):               <ul style="list-style-type: none"> <li>○ 7–24% increase in the Northern Coast Range</li> <li>○ 5–16% increase in the Northern Interior Coast Range</li> <li>○ 10–32% increase in the Klamath Mountains</li> <li>○ 16–43% increase in the Southern Cascades</li> </ul> </li> <li>• Increased CWD and decreased top-level soil moisture is likely even if precipitation increases due to temperature-related changes in evaporative demand (Thorne et al. 2015; Micheli et al. 2018; Pierce et al. 2018)</li> <li>• Drought years are twice as likely to occur over</li> </ul>

<sup>4</sup> Trends in climate factors and natural disturbance regimes presented in this and subsequent summary tables are not species-specific; rather, they represent broad trends and future projections for the study region. The precipitation, temperature, climatic water deficit, and snowpack projections for this project are derived from the Basin Characterization Model, which uses modified Jepson ecoregions (Flint et al. 2013; Flint & Flint 2014). Projections for all other factors are based on a review of relevant studies in the scientific literature. For this project, exposure was evaluated by calculating the magnitude and direction of projected change within the modified Jepson ecoregions that include habitat distribution within the study geography.

Regional Climatic Water Deficit (CWD), Soil Moisture, & Drought Trends <sup>4</sup>	
	<p>the next several decades due to increased co-occurrence of dry years with very warm years (Cook et al. 2015)</p> <ul style="list-style-type: none"> <li>• 80% chance of multi-decadal drought by 2100 under a high-emissions scenario (Cook et al. 2015)</li> <li>• Severe droughts that now occur once every 20 years will occur once every 10 years by 2100 and once-in-a-century drought will occur once every 20 years (Pierce et al. 2018)</li> </ul>
Summary of Potential Impacts on Species <i>(see text for citations)</i>	
<ul style="list-style-type: none"> <li>• Reduced seedling growth and survival under warmer, drier conditions, particularly during periods of drought</li> <li>• Increased mortality in trees experiencing moisture stress, including enhanced vulnerability to drought, bark beetle attack, and disease</li> </ul>	

#### Snowpack amount and timing of snowmelt and runoff

Reduced snowpack and earlier spring snowmelt are likely to increase water stress for sugar pine by accelerating the loss of stored water at high elevations, which reduces growing season soil moisture and leads to longer periods of summer drought (Bales et al. 2011; Gergel et al. 2017). At higher elevations where snowpack persists late into the season, the timing of snowmelt is tied to the beginning of annual growth in sugar pine, and earlier snowmelt has the potential to increase the length of the growing season (Royce & Barbour 2001; Chmura et al. 2011). However, over longer time periods loss of snowpack and earlier onset of the summer drought period can result in a shorter window for annual growth (Royce & Barbour 2001; Chmura et al. 2011).

Earlier snowmelt has also been correlated with increased wildfire activity, including fire size and length of the fire season (Westerling 2016). This is likely due, in part, to reduced fuel moisture in the summer and fall as snow-free periods lengthen (Gergel et al. 2017).

Regional Snowpack & Snowmelt Trends	
<p><i>Historical &amp; current trends:</i></p> <ul style="list-style-type: none"> <li>• 15–39% decrease in April 1 snow water equivalent (SWE) between 1951 and 2010 for the Northwestern California and Southern Cascade ecoregions (Flint et al. 2013)</li> <li>• 15–40-day shift towards earlier date of 90% snowmelt across the western U.S. since 1915 (Hamlet et al. 2005)</li> <li>• 10–30-day shift towards earlier timing of snowmelt-driven runoff across the western</li> </ul>	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> <li>• Decreases in April 1 SWE by 2100 (compared to 1951–1980; Flint et al. 2013; Flint &amp; Flint 2014): <ul style="list-style-type: none"> <li>○ 82–99% decrease in the Northern Coast Range</li> <li>○ 99–100% decrease in the Northern Interior Coast Range</li> <li>○ 72–94% decrease in the Klamath Mountains</li> <li>○ 61–89% decrease in the Southern Cascades</li> </ul> </li> </ul>

Regional Snowpack & Snowmelt Trends	
U.S. since 1948 (Stewart et al. 2005)	<ul style="list-style-type: none"> <li>Likely 5–15-day shift towards earlier timing of snowmelt-driven runoff in northern California by 2100 (up to 60-day shift across the western U.S.; Stewart et al. 2004; Rauscher et al. 2008)</li> </ul>
Summary of Potential Impacts on Species <i>(see text for citations)</i>	
<ul style="list-style-type: none"> <li>Earlier start to the growing season, though this may not result in increased growing potential due to overall drier conditions</li> <li>Reduced soil moisture and longer periods of summer drought, increasing water stress</li> <li>Reduced fuel moisture and longer fire season due to longer snow-free period</li> </ul>	

### Air temperature

Warmer air temperatures primarily impact sugar pine by driving increased evaporative demand, which leads to growth declines and tree mortality associated with increased water stress (Stephenson 1998; van Mantgem & Stephenson 2007; Lutz et al. 2010). Warmer temperatures also contribute to reduced snowpack (Hamlet et al. 2005; Mote et al. 2005; Gergel et al. 2017) and earlier timing of snowmelt (Stewart et al. 2004; Thorne et al. 2015), exacerbating water stress by causing an earlier start and/or longer duration of the annual summer drought period (Royce & Barbour 2001). At higher elevations where trees typically experience less water stress, warmer temperatures may increase growth and productivity (Royce & Barbour 2001; Chmura et al. 2011).

Warmer air temperatures can also increase rates of growth and reproduction in forest pests (e.g., bark beetles) and pathogens (e.g., fungal diseases; Hicke et al. 2006; Bentz et al. 2010; Kliejunas 2011). Because temperature is an important driver of insect development, timing of reproductive cycles, and mortality, warmer temperatures are likely to impact the population dynamics of bark beetles (Hicke et al. 2006; Bentz et al. 2010). For instance, reduced cold-related mortality in bark beetles can increase the likelihood of large-scale insect outbreaks (Hicke et al. 2006; Scheller et al. 2018).

Finally, warmer spring and summer temperatures are significantly correlated with area burned in mid- and high-elevation forests (Keeley & Slyphard 2015; Westerling 2016), likely due to reductions in fuel moisture associated with increasing temperatures (Abatzoglou & Williams 2016).

Regional Air Temperature Trends	
<p><i>Historical &amp; current trends:</i></p> <ul style="list-style-type: none"> <li>0.03°C (0.05°F) decrease to 0.2°C (0.4°F) increase in the average annual temperature between 1900 and 2009 for the Northwestern California, and Southern Cascade ecoregions (Rapacciuolo et al. 2014)</li> </ul>	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> <li>2.2–5.5°C (4.0–9.9°F) increase in the average annual temperature by 2100 (compared to 1951–1980) for the North Coast, Northern Coast Range, Northern Interior Coast Range, Klamath Mountain, and Southern Cascade</li> </ul>

Regional Air Temperature Trends	
<ul style="list-style-type: none"> <li>○ No seasonal temperature trends available</li> </ul>	ecoregions (Flint et al. 2013; Flint & Flint 2014) <ul style="list-style-type: none"> <li>○ 2.0–5.8°C (3.6–10.4°F) increase in average winter minimum temperatures</li> <li>○ 2.2–6.7°C (4.0–12.1°F) increase in average summer maximum temperatures</li> </ul>
Summary of Potential Impacts on Species <i>(see text for citations)</i>	
<ul style="list-style-type: none"> <li>● Increased water stress due to enhanced evaporative demand and temperature-driven changes in snowpack and the timing of snowmelt, especially at lower elevations</li> <li>● Possible increases in growth and productivity at higher elevations that experience less water stress</li> <li>● Increased rates of growth and reproduction for insect pests and pathogens</li> <li>● Increase in annual area burned, likely due to reductions in fuel moisture associated with increasing temperatures</li> </ul>	

### Sensitivity and future exposure to changes in natural disturbance regimes

Regional experts evaluated sugar pine as having moderate-high sensitivity to changes in natural disturbance regimes (high confidence in evaluation), with an overall moderate-high future exposure to these stressors within the study region (low confidence). Key natural disturbance regimes that affect sugar pine include disease, wildfire, and insects.<sup>5</sup>

#### Disease

White pine blister rust, caused by the invasive pathogen *Cronartium ribicola*, was introduced into northern California around 1930 (Maloney 2011) following its arrival in the western U.S. on nursery stock in the early 1900s (McDonald & Hoff 2001). White pine blister rust affects all five-needled pine species, which includes western white pine (*P. monticola*), foxtail pine (*P. balfouriana*), and whitebark pine (*P. albicaulis*), in addition to sugar pine (Tomback & Achuff 2010; Maloney 2011; Dunlap 2012; Krist et al. 2014). *C. ribicola* causes branch dieback, reproductive failure, and eventually mortality in sugar pine (van Mantgem et al. 2004; Sturrock et al. 2011). Stem cankers are especially lethal to small-diameter trees (Smith 1996). Blister rust infection is also frequently associated with bark beetle attacks (van Mantgem et al. 2004; Das et al. 2016). The life cycle of *C. ribicola* requires alternate hosts, many of which are *Ribes* spp. (currents and gooseberries; Kinloch Jr & Scheuner 1990; Geils et al. 2010; Kliejunas 2011), and of which at least 19 species occur in California mixed conifer forests (Kinloch & Scheuner 1990). However, additional alternate hosts have also been recognized, including leafy lousewort (*Pedicularis racemosa*) and giant red Indian paintbrush (*Castilleja miniata*; McDonald et al. 2006). *C. ribicola* spore production and transmission occur in wet, cool conditions, and infections typically occur in wave years when weather conditions are ideal for the fungus (Sturrock et al. 2011). Local site conditions also play a role in infection risk, such as *Ribes* spp. density, mesic forest conditions, and various factors that influence moisture retention on foliage (Kinloch & Scheuner 1990).

---

<sup>5</sup> All disturbance regimes presented were ranked as having a moderate or higher impact on this species.

Many sugar pine populations impacted by white pine blister rust appear to be in decline, and the disease represents a significant threat to long-term sugar pine persistence and genetic diversity (van Mantgem et al. 2004; Tomback & Achuff 2010). Population declines are especially likely where white pine blister rust interacts with other stressors and disturbance, such as increased stand density as a result of fire exclusion that reduces tree vigor and defenses (van Mantgem et al. 2004). A small number of sugar pine trees exhibit complete resistance to white pine blister rust, which is an inherited resistance response typically controlled by a single gene (Sniezko et al. 2008; Dunlap et al. 2018). However, in some cases *C. ribicola* has demonstrated relatively rapid genetic evolution in response to this resistance, resulting in the emergence of more virulent strains that are able to overcome single gene resistance (Kinloch et al. 1999, 2004; Schoettle et al. 2014). Partial resistance, which occurs through a variety of mechanisms that enhance the survival of infected trees, is thought to be controlled by multiple genes and may ultimately prove to be more durable and provide greater opportunities for species response (Sniezko et al. 2008; Kinloch et al. 2012; Vázquez-Lobo et al. 2017; Dunlap et al. 2018).

Changes in temperature and moisture over the coming century are likely to affect the production and transmission of *C. ribicola*, with a warmer, drier climate potentially decreasing spore production and transmission (Kliejunas 2011; Sturrock et al. 2011). The biggest reductions in infection risk are likely to occur outside of the study region in the southern Sierra Nevada (Sturrock et al. 2011), which is also where there is a high frequency of rust resistance (Kinloch 1992; Vuln. Assessment Reviewer, pers. comm., 2018). Less change is expected in cooler, wetter regions such as northern California, and white pine blister rust infections may increase at higher elevations (Millar et al. 2012). However, it is difficult to predict where and how the disease will be impacted by future climate conditions, in part because infection rates depend on the presence of *Ribes* spp., as well as the presence and rate of resistance in sugar pine populations (Vuln. Assessment Reviewer, pers. comm., 2019).

Another concern for sugar pine is dwarf mistletoe (*Arceuthobium* spp.), a parasitic flowering plant that reduces resources available to the tree by using water and photosynthates produced by the host (Kinloch & Scheuner 1990; Hawksworth & Wiens 1996; Kliejunas 2011). Dwarf mistletoe can cause reduced seed and cone production, branch death, and mortality (Hawksworth & Wiens 1996), and infected trees are significantly more susceptible to mortality from secondary stressors such as beetle attack and drought (Kliejunas 2011). Other diseases that can impact sugar pine to varying degrees include Heterobasidion root disease (*Heterobasidion* spp.), black stain root disease (*Leptographium wageneri*), and Armillaria root disease (*Armillaria* spp.; Kliejunas 2011; Safford & Stevens 2017). Dwarf mistletoe and Armillaria root disease, in particular, are likely to become a greater risk under future climate scenarios that include more drought and increasing winter precipitation (Kliejunas 2011).

Regional Disease Trends	
<p><i>Historical &amp; current trends:</i></p> <ul style="list-style-type: none"> <li>Expansion of white pine blister rust across the western U.S. since the early 1900s (McDonald</li> </ul>	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> <li>Range expansion in many diseases as temperatures increase, including dwarf</li> </ul>

Regional Disease Trends	
& Hoff 2001)	mistletoe and white pine blister rust (Kliejunas 2011) <ul style="list-style-type: none"> <li>• Changes in patterns of disease prevalence and/or severity, depending on site conditions and limiting factors of the disease (Kliejunas 2011)</li> </ul>
Summary of Potential Impacts on Species <i>(see text for citations)</i>	
<ul style="list-style-type: none"> <li>• Increased tree damage and mortality due to root rot and other diseases</li> <li>• Reduced seed and cone production in trees impacted by dwarf mistletoe</li> <li>• Population declines in sugar pine due to white pine blister rust in combination with other factors (e.g., mountain pine beetle outbreaks, fire exclusion)</li> </ul>	

### Wildfire

Sugar pine is adapted to frequent fire from a combination of naturally-occurring and human ignitions (Habeck 1992; Norgaard et al. 2016). Historically, forests containing a significant component of sugar pine experienced frequent low- to moderate-intensity fire in drier areas (Skinner & Taylor 2006; Safford & Stevens 2017) and where northern California tribes used cultural burning to promote valued forest resources, including sugar pine (Fry & Stephens 2006; Lake 2007, 2013; Norgaard et al. 2016; Karuk Tribe 2019). In moist forests and those at higher elevations, fires were typically of mixed severity (Bekker & Taylor 2001; Taylor & Skinner 2003),<sup>6</sup> especially within the Klamath region where topographic and geologic complexity is high (Skinner et al. 2006; Perry et al. 2011; Estes et al. 2017). Fire return intervals historically varied between 2 and 22 years (Bekker & Taylor 2001; Taylor & Skinner 2003; Fry & Stephens 2006; Skinner et al. 2009), with greater fire occurrence and extent often associated with cultural burning and periods of drought (Skinner et al. 2009). Following the introduction of widespread fire exclusion and suppression in the early 1900s, fire return intervals lengthened considerably in all forest types where sugar pine is found (Fry & Stephens 2006; Skinner et al. 2009; Steel et al. 2015; Taylor et al. 2016). This has led to shifts in species composition and forest structure that impact sugar pine tree vigor and regeneration (van Mantgem et al. 2004; Zald et al. 2008).<sup>7</sup>

Large sugar pines have several fire-adaptive traits that increase resistance to low- and moderate-intensity fire, including thick bark, deep roots, and a high, open crown (McCune 1988; Habeck 1992; Norgaard et al. 2016). Frequent fire limits shade-tolerant competitors within the understory and encourages sugar pine regeneration by facilitating the release of seeds from the cones and enhancing seedling germination on bare mineral soil in canopy gaps

<sup>6</sup> Definitions of mixed-severity fires vary somewhat, but typically describe irregular patches of low-, moderate-, and high-severity fire. Patch sizes and the proportion of high-severity fire depend on forest type, as well as many other factors that influence fire behavior (e.g., topography, weather, fuel behavior, disturbance history; Hessburg et al. 2007, 2016; Halofsky et al. 2011; Perry et al. 2011). Patches are generally described at an intermediate or stand-level spatial scale, as opposed to individual trees or landscape-scale (Halofsky et al. 2011; Perry et al. 2011).

<sup>7</sup> Refer to the section on non-climate stressors for a more complete discussion of the impacts of fire suppression on sugar pine.

(Habeck 1992; Gray et al. 2005; North et al. 2005; Zald et al. 2008; Norgaard et al. 2016). Routine burning at low- to moderate-intensities also decreases pests and disease, reduces fuel loads to minimize vulnerability of trees to high-severity fires (Habeck 1992; Norgaard et al. 2016), and breaks down organic matter, releasing nutrients to the soils where they become available for plant use (Anderson 1993, 2005; Neary et al. 1999). However, sugar pines can be killed by high-intensity fire (van Mantgem et al. 2004; Skinner et al. 2006), particularly if dense understories increase connectivity between surface and ladder fuels, allowing intense crown fires to occur (Thompson & Spies 2010; Norgaard et al. 2016). Fire-injured trees are also more vulnerable to insect attack (North et al. 2007; Shatford et al. 2007; Maloney et al. 2008; Fettig et al. 2013).

Post-fire establishment usually occurs in the first 1–4 years (North et al. 2005; Donato et al. 2009). Seed dispersal and establishment can be limited in larger high-severity patches (Norgaard et al. 2016), although ample regeneration of sugar pine can occur on some sites at distances over 550 m (1,800 ft; Donato et al. 2009). Seedlings grow rapidly in open areas with full sunlight; this adaptation to recurrent fire allows them to quickly develop thick bark and other fire-resistant characteristics (Safford & Stevens 2017). However, brush and downed woody material can impact sugar pine reestablishment and increase risk of reburning before seedlings mature enough to produce cones (Odion et al. 2010; Norgaard et al. 2016).

<b>Regional Wildfire Trends</b>	
<p><i>Historical &amp; current trends:</i></p> <ul style="list-style-type: none"> <li>• 85% of U.S. Forest Service lands in northern California are burning less frequently compared to pre-1850 fire return intervals, largely due to fire suppression (Safford &amp; Van de Water 2014)</li> <li>• Fire size and total area burned increased on U.S. Forest Service lands in northwestern California between 1910-2008, with the highest values occurring after 2000 (Miller et al. 2012)</li> <li>• Changes in large fires (over 400 ha) in the inland northern California/Sierra Nevada region since the 1970s (Westerling 2016):               <ul style="list-style-type: none"> <li>○ 184–274% increase in frequency</li> <li>○ 270–492% increase in total area burned</li> <li>○ 215% increase in length of the fire season</li> </ul> </li> <li>• Changes in fire size, area burned, and fire frequency over the past several decades remain well below historical tribally-influenced frequency and extent of burning in California (Stephens et al. 2007)</li> <li>• No significant trends in the average areal proportion of high-severity fire were</li> </ul>	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> <li>• State-wide, up to 77% increase in mean annual area burned and 50% increase in the frequency of extremely large fires (&gt;10,000 ha) by 2100 (Westerling 2018)               <ul style="list-style-type: none"> <li>○ Greatest increases in burned area (up to 400%) occur in montane forested areas in northern California (Westerling et al. 2011; Westerling 2018)</li> </ul> </li> <li>• Little projected change in fire severity in northwestern California by 2050 in models based solely on historical fire-climate relationships (Parks et al. 2016)               <ul style="list-style-type: none"> <li>○ However, human activity and fuel buildup from decades of fire suppression have altered historical fire-climate relationships (Taylor et al. 2016; Syphard et al. 2017; Wahl et al. 2019), and projections that incorporate these factors suggest that more significant increases in fire severity and size may occur (Mann et al. 2016; Wahl et al. 2019)</li> </ul> </li> <li>• The majority of impacts to natural and human ecosystems come from extreme fire events</li> </ul>

Regional Wildfire Trends	
<p>documented in northwestern CA from 1984–2008 (Miller et al. 2012; Parks et al. 2015; Law &amp; Waring 2015; Keyser &amp; Westerling 2017)</p> <ul style="list-style-type: none"> <li>○ The relatively short period of record for fire severity data may obscure long-term trends</li> <li>○ To date, there are no peer-reviewed studies on trends in northern California fire severity that include data from the last ten years</li> </ul>	<p>(i.e., fires that have a low probability of occurring in any given place and time), which are likely to increase over the coming century (Westerling 2018)</p> <ul style="list-style-type: none"> <li>○ Generally, these patterns are not well-represented in studies that evaluate indices of mean fire size, intensity/severity, etc.</li> </ul>
Summary of Potential Impacts on Species <i>(see text for citations)</i>	
<ul style="list-style-type: none"> <li>● <b>Immediate:</b> <ul style="list-style-type: none"> <li>○ Facilitates release of seeds from sugar pine cones following fire</li> <li>○ High rates of mortality can occur where fire reaches the canopy via dense ladder fuels</li> </ul> </li> <li>● <b>Short-term (~2-year):</b> <ul style="list-style-type: none"> <li>○ Enhanced sugar pine regeneration due to exposure of mineral soil and removal of understory vegetation that competes with sugar pine for water, nutrients, and light</li> <li>○ Reduced pests and disease following low-intensity fire</li> <li>○ Increased insect predation in trees injured by high-severity fire</li> <li>○ Limited seed dispersal and establishment within the interior of large high-severity patches</li> </ul> </li> <li>● <b>Long-term:</b> <ul style="list-style-type: none"> <li>○ Reduced vulnerability to severe fires when frequent fire limits fuel loads in sugar pine stands</li> <li>○ Maintenance of sugar pines as a component of the landscape</li> <li>○ Increased risk of reburning prior to seedling maturation in areas where brush and downed woody material accumulate</li> </ul> </li> </ul>	

### Insects

Sugar pine can be impacted by many insect species, including mountain pine beetle, red turpentine beetle (*Dendroctonus valens*), pine engraver (*Ips pini*), California fivespined ips (*Ips paraconfusus*), and California flathead borer (*Phaenops californica*; Fettig 2016). Additionally, the sugar pine cone beetle (*Conophthorus lambertianae*) can significantly reduce reproductive success by destroying up to 75% of second-year cones (Kinloch & Scheuner 1990; D. Welty, unpublished data).

Changing climate conditions may impact the prevalence and severity of insect outbreaks by affecting insect development and survival, tree defenses, host susceptibility, and community interactions (Raffa et al. 2008; Bentz et al. 2010; Kliejunas 2011; Sturrock et al. 2011; Weed et al. 2013; Kolb et al. 2016). Insects must overcome a variety of thresholds at multiple spatial and temporal scales in order to cause a large-scale outbreak (Raffa et al. 2008). When these conditions are met, extensive tree mortality can occur at a landscape scale (Fettig et al. 2007; Raffa et al. 2008; Hicke et al. 2016). For instance, bark beetle outbreaks are more likely to occur when the abundance of host species increases and/or forests become denser and more homogenous, largely because competition for water and other resources is greater in these areas (Fettig et al. 2007; Bentz et al. 2010). Water stress reduces tree vigor and impairs defenses by limiting the ability of individual trees to expel attacking insects (Bentz et al. 2010;

Weed et al. 2013; Kolb et al. 2016; Slack et al. 2017). Sugar pine is particularly vulnerable to attack by bark beetles and borers during or after periods of drought when tree vigor is low (Kinloch & Scheuner 1990; Habeck 1992) and insect populations can rapidly increase and move across the landscape attacking drought-stressed trees (Bentz et al. 2010; Weed et al. 2013; Kolb et al. 2016). Conversely, injury from insects and disease can also increase tree vulnerability to drought stress and associated mortality (Kolb et al. 2016). The pitch created as a defense against insect attack is also highly flammable and allows fire to carry more easily, increasing susceptibility to fire-related mortality (Vuln. Assessment Reviewer, pers. comm., 2019).

Warmer temperatures may contribute to earlier bark beetle emergence, the completion of additional life cycles within a single year, reduced cold-related mortality, and expanding distributions for species typically restricted to more southern ranges (Powell & Logan 2005; Hicke et al. 2006; Bentz et al. 2010). Large-scale mountain pine beetle outbreaks are likely to occur when warmer temperatures allow a combination of timing (i.e., emergence at the appropriate time of the season) and synchrony (i.e., life cycle completed in one year) in beetle development (Powell & Logan 2005; Bentz et al. 2010). However, the influence of temperature is non-linear and mountain pine beetles may become more or less synchronous as temperatures increase, resulting in sudden large outbreaks in areas where conditions were previously unfavorable (Powell & Logan 2005; Bentz et al. 2010).

Although some studies have suggested that insect-related tree mortality could impact fire behavior (e.g., spread, intensity, severity) by altering the proportion of large woody fuels to surface fuels (Hicke et al. 2012; Stephens et al. 2018), no clear relationship between insect outbreaks and increased fire activity or severity has been demonstrated in western U.S. forests (Bond et al. 2009; Meigs et al. 2015, 2016; Hart et al. 2015; Reilly & Spies 2016). However, it is possible that insect-related tree mortality can and does impact fire behavior at local scales, but the complex interactions between weather, disturbance history, and numerous other factors likely obscure any consistent relationship across broader spatial and temporal scales.

<b>Regional Insect Outbreak Trends</b>	
<p><i>Historical &amp; current trends:</i></p> <ul style="list-style-type: none"> <li>• Bark beetle outbreaks occurred in most western U.S. forests from 1997–2012, with significant increases in beetle-related mortality after 2000 (peaking from 2008–2012; Hicke et al. 2016)</li> <li>• Compared to other forested areas in the western U.S., northern California experienced relatively low beetle-related mortality during the past two decades (Hicke et al. 2016)</li> </ul>	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> <li>• More severe insect outbreaks are likely as temperatures increase and periods of drought become more frequent (Hicke et al. 2006; Bentz et al. 2010; Kolb et al. 2016)</li> <li>• The average elevation of mountain pine beetle outbreaks is expected to shift upslope, resulting in an overall decrease in the area of forest vulnerable to outbreaks by the end of the century (Williams &amp; Liebhold 2002; Hicke et al. 2006)</li> </ul>
<b>Summary of Potential Impacts on Species</b> <i>(see text for citations)</i>	
<ul style="list-style-type: none"> <li>• Increased tree mortality, especially during and after periods of drought and in dense forest areas</li> </ul>	

## Regional Insect Outbreak Trends

- Shifts in forest composition and structure, reducing landscape-scale heterogeneity

### Dependency on habitat and/or other species

Regional experts evaluated sugar pine as having low dependency on sensitive habitats (high confidence in evaluation) and moderate-high dependency on stand density (moderate confidence). In general, sugar pine was evaluated as having a low degree of specialization (i.e., generalist; high confidence).

Sugar pine occurs across a wide elevational gradient and a broad range of soil types and temperature and precipitation regimes (Kinloch & Scheuner 1990; Habeck 1992; Tomback & Achuff 2010). This species can be found both on steep, rugged slopes and more gentle terrain, as well as on all aspects and on mesic sites with serpentine soils (Kinloch & Scheuner 1990; Habeck 1992; Taylor & Skinner 2003). However, the species fares poorly in dense stands where the ingrowth of shade-tolerant species (e.g., white fir) increases competition for light and soil moisture (van Mantgem et al. 2004). Increased understory density may also enhance susceptibility to white pine blister rust (Vuln. Assessment Workshop, pers. comm., 2017).

### Sensitivity and current exposure to non-climate stressors

Regional experts evaluated sugar pine as having high sensitivity to non-climate stressors (high confidence in evaluation), with an overall moderate-high current exposure to these stressors within the study region (high confidence). Key non-climate stressors that affect sugar pine include fire exclusion (including suppression) and timber harvest.<sup>8</sup>

#### Fire exclusion (including suppression)

Following Euro-American settlement in the 1850s and the implementation of widespread fire suppression beginning in the early 1900s, fire frequency has significantly decreased throughout most northern California forests containing sugar pine (Skinner et al. 2006; Van de Water & Safford 2011; Steel et al. 2015). Over the past century, fire exclusion has increased tree density and canopy cover in stands containing sugar pine (Taylor & Skinner 2003; van Mantgem et al. 2004; Gray et al. 2005; Leonzo & Keyes 2010), inhibiting regeneration and increasing mortality due to competition for light, nutrients, and soil moisture (van Mantgem et al. 2004; Gray et al. 2005; Skinner et al. 2006). Concurrently, recruitment of shade tolerant species such as white fir and incense cedar have increased in fire-excluded forests, shifting species composition by displacing sugar pine and other species adapted to frequent fire (Stuart & Salazar 2000; Taylor & Skinner 2003; Zald et al. 2008; Leonzo & Keyes 2010; Safford & Stevens 2017).

Decreased tree vigor in dense stands can reduce the resistance of sugar pine to disturbances, predisposing existing trees to mortality from drought, bark beetles, and disease (see Table 1; van Mantgem et al. 2004; Leonzo & Keyes 2010; Fettig et al. 2013; Das et al. 2016; Safford &

---

<sup>8</sup> All non-climate stressors presented were ranked as having a moderate or higher impact on this species.

Stevens 2017; Slack et al. 2017). The presence of surface and ladder fuels has also increased dramatically in the absence of frequent fires that historically limited fuel loading and maintained more open forest structures (Safford & Stevens 2017). Under these conditions, fires that escape containment are more likely to be severe and spread quickly over large areas (Taylor & Skinner 2003; Spies et al. 2006; Halofsky et al. 2014; Steel et al. 2015; North et al. 2016), particularly during periods of extreme fire weather (Cocking et al. 2015). Fuel loading around the base of individual trees and fire cavities in tree trunks that have built up woody rot material can also increase the susceptibility of an individual tree to thermal trauma (i.e., increased burning-heat residence time, thermal girdling with cambium tissue or weakening structurally the tree’s trunk; Vuln. Assessment Reviewer, pers. comm., 2019).

Finally, individual sugar pines can be damaged or destroyed during fire suppression activities such as fire line construction and back burning (Lake 2013; Nesmith et al. 2015; Norgaard et al. 2016). These include large, old trees with high ecological and cultural value (Lake 2013; Norgaard et al. 2016). For instance, trees that pose hazards to firefighters or that have higher levels of easily-ignited bark surface pitch may be preemptively felled to limit the spread of severe fires (Norgaard et al. 2016). Larger dead sugar pines, which may also be ecologically and culturally important, are also more likely to be targeted during post-fire salvage logging operations due to their high economic value (Norgaard et al. 2016).

**Table 1.** Impacts of fire suppression on the resilience of sugar pine to climate stressors and climate-driven changes in fire regimes (table adapted from Norgaard et al. 2016).

Prior to Fire	During Fire	After Fire
<ul style="list-style-type: none"> <li>• Increases competition for resources (e.g., soil moisture)</li> <li>• Reduces germination</li> <li>• Increases incidence of disease</li> </ul>	<ul style="list-style-type: none"> <li>• Increased likelihood of damage or loss due to fire itself and/or fire suppression activities</li> </ul>	<ul style="list-style-type: none"> <li>• Larger dead trees in high severity fire areas (which may also be culturally and/or ecologically important) may be targeted for salvage logging</li> </ul>
Source(s): van Mantgem et al. 2004; Gray et al. 2005; Lake 2013; Norgaard et al. 2016		

### Timber harvest

Sugar pine is among the most valuable species harvested for timber due to its large size, straight trunk, and distinctive wood (Kinloch 1984; Zeglen et al. 2010). Current harvest on privately-owned lands largely driven by residential construction (Kinloch Jr 1984; Vuln. Assessment Workshop, pers. comm., 2017).

Widespread logging began during the California Gold Rush of 1849, as demand for lumber rapidly increased (Cermak 1996). By the late 1800s, the largest trees had already been harvested (Kinloch 1984). In the absence of fire, harvested areas shifted towards denser, more homogenous stands dominated by shade-tolerant species, including white fir and incense cedar (Safford & Stevens 2017). This resulted shifts in species composition and an overall simplification of forest structure (Safford & Stevens 2017).

---

## Adaptive Capacity

Sugar pine was evaluated by regional experts as having moderate overall adaptive capacity (moderate confidence in evaluation).

### Species extent, status, connectivity, and dispersal ability

Regional experts evaluated sugar pine as having a high geographic extent (high confidence in evaluation), relatively strong and healthy population status (moderate confidence), and a moderate degree of connectivity between populations (moderate confidence).

Regional experts evaluated sugar pine as having a moderate-high dispersal ability (moderate confidence in evaluation). Barriers to dispersal were evaluated as having a moderate-high impact on the species (high confidence). Geologic features, fast-growing understory trees (e.g., Douglas-fir, incense cedar, white fir), and timber harvest/clear-cuts were identified as the primary barriers to dispersal.<sup>9</sup>

Despite their wide distribution and broad ecological tolerance, sugar pine populations have declined in many areas due to a combination of selective logging, fire exclusion, and disease (van Mantgem et al. 2004; Gray et al. 2005; Skinner et al. 2006; Maloney et al. 2011; Safford & Stevens 2017). Although studies have not found consistent population-level effects, ongoing losses of sugar pine and reduced regeneration rates in fire-excluded forests impacted by white pine blister rust threaten the persistence of the species (van Mantgem et al. 2004).

Sugar pine seeds are primarily dispersed by wind, but because seeds are large and heavy compared to other winged pine seeds, they generally do not disperse far (Habeck 1992; Johnson et al. 2003), with up to 80% of seeds falling within 30 m (100 ft) of the source tree (Kinloch & Scheuner 1990; Habeck 1992). Longer-distance dispersal can be facilitated by small mammals and birds that gather and hoard seeds (Vander Wall 2003; Thayer & Vander Wall 2005), which largely compensates for the short distance traveled by wind-dispersed seeds (Vander Wall 2003).

### Intraspecific/life history diversity

Regional experts evaluated sugar pine as having low life history diversity (high confidence in evaluation), high genetic diversity (high confidence), and moderate-high phenotypic plasticity (moderate confidence).

Historically, sugar pines harbored high levels of genetic and phenotypic diversity, increasing the potential for the development of adaptive traits (Eckert et al. 2015; Vangestel et al. 2016). This potential is further enhanced by their broad latitudinal distribution and ecological tolerance (Schierenbeck 2017). Multiple studies have found evidence of local adaptation to stressors such

---

<sup>9</sup> All barriers presented were ranked as having a moderate or higher impact on this species.

as drought and disease across populations (Eckert et al. 2015; Vangestel et al. 2016). For instance, in a landscape study of sugar pine in the Lake Tahoe Basin, Eckert et al. (2015) and Maloney et al. (2019) found that sugar pine was locally adapted with abundant genetic and phenotypic variation.

### Resistance and recovery

Regional experts evaluated sugar pine as having low-moderate resistance to climate stressors and natural disturbance regimes (low confidence in evaluation). Population recovery potential (i.e., recruitment rate) was evaluated as low-moderate (low confidence).

Sugar pine is a drought-tolerant and fire-adapted species that is well-adapted to the climate of northern California. It also appears to be more resistant to extreme storms than many co-occurring species (e.g., true firs; Vuln. Assessment Workshop, pers. comm., 2017). However, a century of fire exclusion across the species' range has reduced tree vigor due to enhanced competition for soil moisture, light, and nutrients (van Mantgem et al. 2004; Young et al. 2017; Slack et al. 2017). Stressed trees have decreased resistance to drought, disease, insect attack, and fire-related mortality, particularly on dry sites (van Mantgem et al. 2004, 2009; van Mantgem & Stephenson 2007; Young et al. 2017; Slack et al. 2017). Warmer, drier future conditions associated with climate change may cause higher rates of mortality in existing sugar pine populations and limit resistance to fire, insect attack, and other disturbance (van Mantgem & Stephenson 2007; Lutz et al. 2010; van Mantgem et al. 2013; Slack et al. 2017). Further loss of genetic diversity due to white pine blister rust may also reduce the potential for adaptive traits such as resistance to pests and disease (Tomback & Achuff 2010).

Sugar pine requires about 30 years to reach reproductive maturity and start producing cones (Vuln. Assessment Reviewer, pers. comm., 2019). However, it can take around 150 years for trees to become good cone producers (occurs at diameters of roughly 75 cm [30 in]; Kinloch Jr & Scheuner 1990). Mature trees can produce very large amounts of seed (average of 150 seeds per cone), and cones are shed between late August and the end of October, depending on elevation (Kinloch & Scheuner 1990; Habeck 1992). Between 28% and 99% percent of seeds produced are sound, depending on the crop year (Kinloch & Scheuner 1990; Habeck 1992). Observations also suggest that sugar pines produce better seed crops in the first few years following low- to moderate-severity fire (F. Lake, pers. comm., 2019). Although many seeds are produced, seed viability within soil seed banks may be short (Kinloch Jr & Scheuner 1990; Vuln. Assessment Workshop, pers. comm., 2017).

In general, sugar pine regeneration is synchronized with both climate and fire, occurring primarily during wet years and in burned areas (North et al. 2005; Young & Latimer 2017). Although seedling recruitment is highest on bare mineral soil, sugar pine is moderately shade-tolerant and can also regenerate on forest litter within small canopy gaps which suggests that relatively low levels of canopy disturbance are required to maintain this species (Gray et al. 2005). Seedling survival is increased in patches of ceanothus and manzanita, perhaps because they offer some shade to protect vulnerable seedlings (Gray et al. 2005). However, sugar pine

seedling mortality is often high, primarily due to desiccation, insects, and rodent herbivory (Kinloch & Scheuner 1990; Habeck 1992; Gray et al. 2005).

## Management potential

### *Public and societal value*

Regional experts evaluated sugar pine as having moderate-high public and societal value (high confidence in evaluation).

Sugar pine cones, which are among the largest of any conifer, are highly valued by the public for aesthetic, decorative, and commercial purposes (Kinloch Jr 1984; Vuln. Assessment Workshop, pers. comm., 2018). Sugar pines also have very high timber market value (Kinloch 1984; Zeglen et al. 2010), which has contributed to research interest in the species, which is relatively well-studied (Vuln. Assessment Workshop, pers. comm., 2018).

Sugar pines hold great importance for northern California tribes, who utilize the tree as a traditional food resource and for other subsistence, ceremonial, and spiritual uses (Driver 1939; Kroeber & Gifford 1949; Schenck & Gifford 1952; Lake 2013; Norgaard et al. 2016; Karuk Tribe 2019), and preserving large sugar pines is crucial to maintain their ecological and cultural role on the landscape (Karuk DNR 2009). However, many of the cultural services historically provided by sugar pine have declined since Euro-American settlement and subsequent logging and the implementation of fire suppression practices (Lake 2013; Norgaard et al. 2016). Advocacy by tribal members may be an important driver of societal support for management of the species (Vuln. Assessment Workshop, pers. comm., 2018).

### *Management capacity and ability to alleviate impacts<sup>10</sup>*

Regional experts evaluated the potential for reducing climate impacts on sugar pine through management as high (high confidence in evaluation).

High genetic diversity and fire tolerant traits increase the potential for management strategies to alleviate some climate impacts on sugar pine (Vuln. Assessment Workshop, pers. comm., 2018). Silvicultural treatments are currently being used to enhance the sugar pine forest component in northern California through methods such as prescribed fire, mechanical thinning, and regeneration (Vuln. Assessment Workshop, pers. comm., 2018). On public lands, the general management strategy for sugar pine includes favoring and retaining sugar pine in thinning treatments, pruning to reduce susceptibility to blister rust, and collection/breeding programs to identify and propagate trees resistant to stressors such as disease (Vuln. Assessment Reviewer, pers. comm., 2018). Restoration that focuses on supporting tribal values and management (e.g., cultural burning) is also likely to increase social and ecological resilience to changes in climate conditions, including disease, drought, and uncharacteristically severe fires (Long et al. 2014; Long & Lake 2018; Karuk Tribe 2019).

---

<sup>10</sup> Further information on climate adaptation strategies and actions for northern California can be found on the project page (<https://bit.ly/31AUGs5>).

Reducing forest density through fire and/or mechanical thinning would likely reduce resource competition, increase tree vigor, and encourage the development of larger trees with fire-resistant characteristics (Latham & Tappeiner 2002; van Mantgem et al. 2004; North et al. 2009; Karuk Tribe 2019). Studies also suggest that reducing forest density through the use of prescribed fire may also increase resistance to drought (van Mantgem et al. 2016). Reintroducing a more natural fire regime is particularly critical in fire-adapted forests containing a sugar pine component, and would likely increase sugar pine growth and recruitment and reduce vulnerability to more frequent, severe fires by promoting a more open forest understory (see Table 2; van Mantgem et al. 2004; Karuk Tribe 2019).

**Table 2.** Effects of prescribed fire on sugar pine across time (table adapted from Norgaard et al. 2016). Cultural burning practices, in particular, have played a role in maintaining this species on the landscape over very long time scales.

Immediate	2-Year	Long Term
<ul style="list-style-type: none"> <li>• Exposes mineral soil that may benefit sugar pine germination</li> <li>• Facilitates release of sugar pine seeds from cones</li> <li>• Reduces competition for water, nutrients, and light following the removal of understory vegetation</li> </ul>	<ul style="list-style-type: none"> <li>• Reduces disease and encourages regeneration while protecting mature trees</li> <li>• Increases nut quality by reducing pests</li> </ul>	<ul style="list-style-type: none"> <li>• Protects stands by decreasing fuel loads, reducing the severity of future wildfires</li> <li>• Maintains sugar pine as a component of the landscape</li> </ul>
Source(s): Habeck 1992; Norgaard et al. 2016; Karuk Tribe 2019		

Among the most pressing management needs for sugar pine is limiting losses to white pine blister rust, which has the potential to threaten the persistence of this species (Tomback & Achuff 2010; Zeglen et al. 2010). Initially, disease control efforts were focused on *Ribes* eradication (Maloy 1997; Zeglen et al. 2010), but in the 1960s these programs were largely discontinued in the western U.S. due to high costs and labor, as well as the difficulty of eliminating common native plant species across such large areas (Maloy 1997). As it has become increasingly clear that the threat of white pine blister rust cannot be eliminated (Maloy 1997), proactive interventions have refocused on increasing the frequency of rust-resistance in sugar pine populations and preventing severe population declines (Schoettle & Sniezko 2007). The most effective strategies are likely to involve concurrent efforts to manage both currently impacted areas and those that are likely to be impacted in the future, and may include:

- Local *Ribes* control in accessible, high-value areas, which may reduce the frequency of wave years and slow disease impacts to buy more time for the development and implementation of other management strategies (e.g., increasing rust resistance; Schoettle & Sniezko 2007);
- Introducing rust-resistant stock by identifying host genotypes with full or partial resistance (though the availability of seeds with partial resistance are limited), followed

by seed collection and/or artificial regeneration (Schoettle & Sniezko 2007; Dunlap et al. 2018);

- Using rust-resistant stock in replanting projects following fire or restoration forest thinning (Vuln. Assessment Reviewer, pers. comm., 2019); and
- Restoring frequent fire and diversifying sugar pine age class structure in forests not yet impacted by white pine blister rust, which would enhance regeneration and tree vigor, allowing more efficient natural selection of blister rust resistance in young trees while older trees sustain ecosystem function (Sniezko et al. 2004; Schoettle & Sniezko 2007).

### *Ecosystem services*

Sugar pine provides a variety of ecosystem services:

- Provisioning of food, fiber, lumber for construction, fuel, genetic resources, and ornamental resources;
- Regulation of air quality, climate/microenvironments (e.g., shade), flood/erosion control, water purification, pollination (in understory species), and fire hazard reduction;
- Support of wildlife habitat, primary production, oxygen production, soil formation/retention, carbon sequestration, nutrient cycling, and water cycling; and
- Cultural/tribal uses for spiritual/religious purposes, knowledge systems, educational values, aesthetic values, sense of place, cultural heritage, inspiration, and recreation (Vuln. Assessment Workshop, pers. comm., 2017).

### Recommended Citation

Hilberg LE, Reynier WA, Kershner JM. 2019. Sugar Pine (*Pinus lambertiana*): Northern California Climate Change Vulnerability Assessment Synthesis. Version 1.0. EcoAdapt, Bainbridge Island, WA.

Further information on the Northern California Climate Adaptation Project is available on the project website (<https://tinyurl.com/NorCalAdaptation>).

### Literature Cited

- Abatzoglou JT, Williams AP. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* **113**:11770–11775.
- Allen CD et al. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* **259**:660–684.
- American Forests. 2018. Champion Tree National Register. Available from <https://www.americanforests.org/big-trees/> (accessed January 23, 2019).
- Anderson MK. 1993. Native Californians as ancient and contemporary cultivators. Pages 151–174 in T. C. Blackburn and K. Anderson, editors. *Before the wilderness: environmental management by native Californians*. Balena Press, Menlo Park, CA.
- Anderson MK. 2005. *Tending the wild: Native American knowledge and the management of California's natural resources*. University of California Press, Berkeley, CA.

- Angell N, Waring KM, Graves TA. 2014. Predicting height growth of sugar pine regeneration using stand and individual tree characteristics. *Forestry: An International Journal of Forest Research* **87**:85–98.
- Bales RC, Hopmans JW, O’Geen AT, Meadows M, Hartsough PC, Kirchner P, Hunsaker CT, Beaudette D. 2011. Soil moisture response to snowmelt and rainfall in a Sierra Nevada mixed-conifer forest. *Vadose Zone Journal* **10**:786–799.
- Bekker MF, Taylor AH. 2001. Gradient analysis of fire regimes in montane forests of the southern Cascade Range, Thousand Lakes Wilderness, California, USA. *Plant Ecology* **155**:15–28.
- Bentz BJ, Regniere J, Fettig CJ, Hansen EM, Hayes JL, Hicke JA, Kelsey RG, Negron JF, Seybold SJ. 2010. Climate change and bark beetles of the western United States and Canada: direct and indirect effects. *BioScience* **60**:602–613.
- Bond ML, Lee DE, Bradley CM, Hanson CT. 2009. Influence of pre-fire tree mortality on fire severity in conifer forests of the San Bernardino Mountains, California. *The Open Forest Science Journal* **2**:41–47.
- Calflora. 2019. Calflora: information on California plants for education, research and conservation, with data contributed by public and private institutions and individuals, including the Consortium of California Herbaria [web application]. The Calflora Database [a non-profit organization], Berkeley, CA. Available from <http://www.calflora.org/> (accessed January 2, 2019).
- Cermak RW. 1996. Sugar pine in the history of the West Coast. Pages 10–21 in B. B. Kinloch Jr., M. Marosy, and M. E. Huddleston, editors. *Sugar pine: status, values, and roles in ecosystems*. Davis, CA, 1992 March 30–April 1. Publ. 3362. University of California, Division of Agriculture and Natural Resources, Davis, CA.
- Chmura DJ, Anderson PD, Howe GT, Harrington CA, Halofsky JE, Peterson DL, Shaw DC, Brad St. Clair J. 2011. Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. *Forest Ecology and Management* **261**:1121–1142.
- CNPS. 2019. A manual of California vegetation, online edition. California Native Plant Society Press. Available from <http://www.cnps.org/cnps/vegetation/> (accessed January 2, 2019).
- Cocking MI, Varner JM, Engber EA. 2015. Conifer encroachment in California oak woodlands. Pages 505–514 in R. B. Standiford and K. L. Purcell, editors. *Proceedings of the seventh California oak symposium: managing oak woodlands in a dynamic world*. Gen. Tech. Rep. PSW-GTR-251. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
- Cook BI, Ault TR, Smerdon JE. 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances* **1**:e1400082.
- Das AJ, Stephenson NL, Davis KP. 2016. Why do trees die? Characterizing the drivers of background tree mortality. *Ecology* **97**:2616–2627.
- Diffenbaugh NS, Swain DL, Touma D. 2015. Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences* **112**:3931–3936.
- Dobrowski SZ. 2011. A climatic basis for microrefugia: the influence of terrain on climate. *Global Change Biology* **17**:1022–1035.
- Dobrowski SZ, Swanson AK, Abatzoglou JT, Holden ZA, Safford HD, Schwartz MK, Gavin DG. 2015. Forest structure and species traits mediate projected recruitment declines in western US tree species. *Global Ecology and Biogeography* **24**:917–927.
- Donato DC, Fontaine JB, Campbell JL, Robinson WD, Kauffman JB, Law BE. 2009. Conifer regeneration in stand-replacement portions of a large mixed-severity wildfire in the Klamath–Siskiyou Mountains. *Canadian Journal of Forest Research* **39**:823–838.
- Driver HE. 1939. Culture element distributions: X northwest California. University of California *Anthropological Records* **1**:297–433.

- Dunlap J, Burton D, Davis D, Vogler DR, Westfall B. 2018. Sugar pine (*Pinus lambertiana*) partial resistance heritability study. Page 162 in A. W. Schoettle, R. A. Sniezko, and J. T. Kliejunas, editors. Proceedings of the IUFRO joint conference: genetics of five-needle pines, rusts of forest trees, and strobosphere; 2014 June 15-20; Fort Collins, CO. Proc. RMRS-P-76. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Dunlap JM. 2012. Variability in and environmental correlates to white pine blister rust incidence in five California white pine species. *Northwest Science* **86**:248–263.
- Eckert AJ, Maloney PE, Vogler DR, Jensen CE, Delfino-Mix A, Neale DB. 2015. Local adaptation at fine spatial scales: an example from sugar pine (*Pinus lambertiana*, Pinaceae). *Tree Genetics & Genomes* **11**:42.
- Estes BL, Knapp EE, Skinner CN, Miller JD, Preisler HK. 2017. Factors influencing fire severity under moderate burning conditions in the Klamath Mountains, northern California, USA. *Ecosphere* **8**:e01794.
- Fettig CJ. 2016. Native bark beetles and wood borers in Mediterranean forests of California. Pages 499–528 in T. D. Paine and F. Lieutier, editors. *Insects and diseases of Mediterranean forest systems*. Springer International Publishing, Switzerland.
- Fettig CJ, Klepzig KD, Billings RF, Munson AS, Nebeker TE, Negrón JF, Nowak JT. 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. *Forest Ecology and Management* **238**:24–53.
- Fettig CJ, Mortenson LA, Bulaon BM, Foulk PB. 2019. Tree mortality following drought in the central and southern Sierra Nevada, California, U.S. *Forest Ecology and Management* **432**:164–178.
- Fettig CJ, Reid ML, Bentz BJ, Sevanto S, Spittlehouse DL, Wang T. 2013. Changing climates, changing forests: a western North American perspective. *Journal of Forestry* **111**:214–228.
- Flint LE, Flint AL. 2014. California Basin Characterization Model: a dataset of historical and future hydrologic response to climate change (Ver. 1.1, May 2017). U.S. Geological Survey Data Release. Available from <https://doi.org/10.5066/F76T0JPB>.
- Flint LE, Flint AL, Thorne JH, Boynton R. 2013. Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance. *Ecological Processes* **2**:25.
- Fry DL, Stephens SL. 2006. Influence of humans and climate on the fire history of a ponderosa pine-mixed conifer forest in the southeastern Klamath Mountains, California. *Forest Ecology and Management* **223**:428–438.
- Geils BW, Hummer KE, Hunt RS. 2010. White pines, *Ribes*, and blister rust: a review and synthesis. *Forest Pathology* **40**:147–185.
- Gergel DR, Nijssen B, Abatzoglou JT, Lettenmaier DP, Stumbaugh MR. 2017. Effects of climate change on snowpack and fire potential in the western USA. *Climatic Change* **141**:287–299.
- Gray AN, Zald HSJ, Kern RA, North M. 2005. Stand conditions associated with tree regeneration in Sierran mixed-conifer forests. *Forest Science* **51**:198–210.
- Griffin D, Anchukaitis KJ. 2014. How unusual is the 2012–2014 California drought? *Geophysical Research Letters* **41**:9017–9023.
- Habeck RJ. 1992. *Pinus lambertiana*. In: *Fire Effects Information System* [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available from <https://www.fs.fed.us/database/feis/plants/tree/pinlam/all.html> (accessed October 12, 2018).
- Halofsky JE et al. 2011. Mixed-severity fire regimes: lessons and hypotheses from the Klamath-Siskiyou Ecoregion. *Ecosphere* **2**:1–19.

- Halofsky JS, Halofsky JE, Burcsu T, Hemstrom MA. 2014. Dry forest resilience varies under simulated climate-management scenarios in a central Oregon, USA landscape. *Ecological Applications* **24**:1908–1925.
- Hamlet AF, Mote PW, Clark MP, Lettenmaier DP. 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. *Journal of Climate* **18**:4545–4561.
- Hart SJ, Schoennagel T, Veblen TT, Chapman TB. 2015. Area burned in the western United States is unaffected by recent mountain pine beetle outbreaks. *Proceedings of the National Academy of Sciences* **112**:4375–4380.
- Hawksworth FG, Wiens D. 1996. Dwarf mistletoes: biology, pathology, and systematics. *Agriculture Handbook* 709. U.S. Department of Agriculture, Forest Service, Washington, D.C.
- Hessburg PF et al. 2016. Tamm Review: management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. *Forest Ecology and Management* **366**:221–250.
- Hessburg PF, Salter RB, James KM. 2007. Re-examining fire severity relations in pre-management era mixed conifer forests: inferences from landscape patterns of forest structure. *Landscape Ecology* **22**:5–24.
- Hicke JA, Johnson MC, Hayes JL, Preisler HK. 2012. Effects of bark beetle-caused tree mortality on wildfire. *Forest Ecology and Management* **271**:81–90.
- Hicke JA, Logan JA, Powell J, Ojima DS. 2006. Changing temperatures influence suitability for modeled mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the western United States. *Journal of Geophysical Research: Biogeosciences* **111**:G02019.
- Hicke JA, Meddens AJH, Kolden CA. 2016. Recent tree mortality in the western United States from bark beetles and forest fires. *Forest Science* **62**:141–153.
- Johnson M, Vander Wall SB, Borchert M. 2003. A comparative analysis of seed and cone characteristics and seed-dispersal strategies of three pines in the subsection Sabinianae. *Plant Ecology* **168**:69–84.
- Kaiser KE, McGlynn BL, Emanuel RE. 2013. Ecohydrology of an outbreak: mountain pine beetle impacts trees in drier landscape positions first. *Ecohydrology* **6**:444–454.
- Karuk DNR. 2009. Eco-cultural resources management plan. Karuk Tribe Department of Natural Resources, Orleans, CA.
- Karuk Tribe. 2019. Karuk Climate Adaptation Plan. Karuk Tribe, Orleans, CA. Available from <https://karuktribeclimatechangeprojects.com/climate-adaptation-plan/> (accessed August 22, 2019).
- Keeley JE, Syphard AD. 2015. Different fire–climate relationships on forested and non-forested landscapes in the Sierra Nevada ecoregion. *International Journal of Wildland Fire* **24**:27–36.
- Keyser A, Westerling AL. 2017. Climate drives inter-annual variability in probability of high severity fire occurrence in the western United States. *Environmental Research Letters* **12**:065003.
- Kinloch BB Jr. 1984. Sugar pine: an American wood. FS-257. U.S. Department of Agriculture, Forest Service, Information Services, Washington, D.C. Available from <http://www.fpl.fs.fed.us/documnts/usda/amwood/257sugpi.pdf> (accessed October 29, 2018).
- Kinloch BB Jr. 1992. Distribution and frequency of a gene for resistance to white pine blister rust in natural populations of sugar pine. *Canadian Journal of Botany* **70**:1319–1323.
- Kinloch BB Jr, Burton D, Davis DA, Westfall RD, Dunlap J, Vogler DR. 2012. Strong partial resistance to white pine blister rust in sugar pine. Pages 80–91 in R. A. Snieszko, A. D. Yanchuk, J. T. Kliejunas, K. M. Palmieri, J. M. Alexander, and S. J. Frankel, editors. *Proceedings of the fourth international workshop on the genetics of host-parasite interactions in forestry: disease and insect resistance in forest trees*. Gen. Tech. Rep. PSW-GTR-240. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.

- Kinloch BB Jr, Scheuner WH. 1990. *Pinus lambertiana* Dougl. - sugar pine. Pages 370–379 in R. M. Burns and B. H. Honkala, editors. *Silvics of North America. Volume 1: Conifers*. Agriculture Handbook 654. U.S. Department of Agriculture, Forest Service, Washington, D.C.
- Kinloch BB Jr, Sniezko RA, Barnes GD, Greathouse TE. 1999. A major gene for resistance to white pine blister rust in western white pine from the western Cascade Range. *Phytopathology* **89**:861–867.
- Kinloch BB Jr, Sniezko RA, Dupper GE. 2004. Virulence gene distribution and dynamics of the white pine blister rust pathogen in western North America. *Phytopathology* **94**:751–758.
- Kliejunas JT. 2011. A risk assessment of climate change and the impact of forest diseases on forest ecosystems in the western United States and Canada. Gen. Tech. Rep. PSW-GTR-236. U.S. Department of Agriculture, Forest Service, Pacific Southwest Station, Albany, CA.
- Kolb TE, Fettig CJ, Ayres MP, Bentz BJ, Hicke JA, Mathiasen R, Stewart JE, Weed AS. 2016. Observed and anticipated impacts of drought on forest insects and diseases in the United States. *Forest Ecology and Management* **380**:321–334.
- Krist FJ, Ellenwood JR, Woods ME, McMahan AJ, Cowardin JP, Ryerson DE, Sapio FJ, Sweifler MO, Romero SA. 2014. 2013–2027 National Insect and Disease Forest Risk Assessment. FHTET 14-01. U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team, Fort Collins, CO.
- Kroeber AL, Gifford EW. 1949. World renewal: a cult system of Native Northwest California. *Anthropological Records* Vol. 13, No. 1. University of California Press, Berkeley and Los Angeles, CA.
- Lake FK. 2007. Traditional ecological knowledge to develop and maintain fire regimes in northwestern California, Klamath-Siskiyou bioregion: management and restoration of culturally significant habitats. Ph.D dissertation. Oregon State University, Corvallis, OR.
- Lake FK. 2013. Trails, fires, and tribulations: tribal resource management and research issues in Northern California. *Occasion: Interdisciplinary Studies in the Humanities* **5**:22.
- Latham P, Tappeiner JC II. 2002. Response of old-growth conifers to reduction in stand density in western Oregon forests. *Tree Physiology* **22**:137–146.
- Law BE, Waring RH. 2015. Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests. *Forest Ecology and Management* **355**:4–14.
- Legras EC, Vander Wall SB, Board DI. 2010. The role of germination microsite in the establishment of sugar pine and Jeffrey pine seedlings. *Forest Ecology and Management* **260**:806–813.
- Leonzo CM, Keyes CR. 2010. Fire-excluded relict forests in the southeastern Klamath Mountains, California, USA. *Fire Ecology* **6**:62–76.
- Long JW, Lake FK. 2018. Escaping social-ecological traps through tribal stewardship on national forest lands in the Pacific Northwest, United States of America. *Ecology and Society* **23**:10.
- Long JW, Quinn-Davidson L, Skinner CN. 2014. Science synthesis to support socioecological resilience in the Sierra Nevada and southern Cascade Range. Gen. Tech. Rep. PSW-GTR-247. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
- Lutz JA, van Wagtenonk JW, Franklin JF. 2010. Climatic water deficit, tree species ranges, and climate change in Yosemite National Park. *Journal of Biogeography* **37**:936–950.
- Maloney PE. 2011. Incidence and distribution of white pine blister rust in the high-elevation forests of California. *Forest Pathology* **41**:308–316.
- Maloney PE, Eckert AJ, Vogler DR, Jensen CE, Delfino-Mix A. 2019. Ecological genetics of the white pine species from the Lake Tahoe Basin, USA: implications for conservation and evolutionary potential **Manuscript in revision**.
- Maloney PE, Smith TF, Jensen CE, Innes J, Rizzo DM, North MP. 2008. Initial tree mortality and insect and pathogen response to fire and thinning restoration treatments in an old-growth mixed-conifer forest of the Sierra Nevada, California. *Canadian Journal of Forest Research* **38**:3011–3020.

- Maloney PE, Vogler DR, Eckert AJ, Jensen CE, Neale DB. 2011. Population biology of sugar pine (*Pinus lambertiana* Dougl.) with reference to historical disturbances in the Lake Tahoe Basin: implications for restoration. *Forest Ecology and Management* **262**:770–779.
- Maloy OC. 1997. White pine blister rust control in North America: a case history. *Annual Review of Phytopathology* **35**:87–109.
- Mann ML, Batllori E, Moritz MA, Waller EK, Berck P, Flint AL, Flint LE, Dolfi E. 2016. Incorporating anthropogenic influences into fire probability models: effects of human activity and climate change on fire activity in California. *PLoS ONE* **11**:e0153589.
- McCune B. 1988. Ecological diversity in North American pines. *American Journal of Botany* **75**:353–368.
- McDonald GI, Hoff RJ. 2001. Blister rust: an introduced plague. Pages 193–220 in D. F. Tomback, S. F. Arno, and R. E. Keane, editors. *Whitebark pine communities: ecology and restoration*. Island Press, Washington, D.C.
- McDonald GI, Richardson BA, Zambino PJ, Klopfenstein NB, Kim M-S. 2006. *Pedicularis* and *Castilleja* are natural hosts of *Cronartium ribicola* in North America: a first report. *Forest Pathology* **36**:73–82.
- Meigs GW, Campbell JL, Zald HSJ, Bailey JD, Shaw DC, Kennedy RE. 2015. Does wildfire likelihood increase following insect outbreaks in conifer forests? *Ecosphere* **6**:1–24.
- Meigs GW, Zald HSJ, Campbell JL, Keeton WS, Kennedy RE. 2016. Do insect outbreaks reduce the severity of subsequent forest fires? *Environmental Research Letters* **11**:045008.
- Micheli E, Dodge C, Flint L, Comendant T. 2018. Climate and natural resource analyses and planning for the North Coast Resource Partnership: a technical memorandum summarizing data products. A final report prepared by the Dwight Center for Conservation Science at Pepperwood, Santa Rosa, CA, for West Coast Watershed and the North Coast Resource Partnership.
- Millar CI, Westfall RD, Delany DL, Bokach MJ, Flint AL, Flint LE. 2012. Forest mortality in high-elevation whitebark pine (*Pinus albicaulis*) forests of eastern California, USA: influence of environmental context, bark beetles, climatic water deficit, and warming. *Canadian Journal of Forest Research* **42**:749–765.
- Miller JD, Skinner CN, Safford HD, Knapp EE, Ramirez CM. 2012. Trends and causes of severity, size, and number of fires in northwestern California, USA. *Ecological Applications* **22**:184–203.
- Monleon VJ, Lintz HE. 2015. Evidence of tree species' range shifts in a complex landscape. *PLoS ONE* **10**:e0118069.
- Mote PW, Hamlet AF, Clark MP, Lettenmaier DP. 2005. Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society* **86**:39–49.
- Nearly DG, Klopatek CC, DeBano LF, Ffolliott PF. 1999. Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management* **122**:51–71.
- Nesmith JCB, Das AJ, O'Hara KL, van Mantgem PJ. 2015. The influence of prefire tree growth and crown condition on postfire mortality of sugar pine following prescribed fire in Sequoia National Park. *Canadian Journal of Forest Research* **45**:910–919.
- Norgaard KM, Vinyeta K, Hillman L, Tripp B, Lake F. 2016. Karuk Tribe climate vulnerability assessment: assessing vulnerabilities from the increased frequency of high severity fire. Karuk Tribe Department of Natural Resources, Orleans, CA.
- North M, Collins B, Safford H, Stephenson NL. 2016. Montane forests. Pages 553–577 in H. Mooney and E. Zavaleta, editors. *Ecosystems of California*. University of California Press, Oakland, CA.
- North M, Hurteau M, Fiegenger R, Barbour M. 2005. Influence of fire and El Niño on tree recruitment varies by species in Sierran mixed conifer. *Forest Science* **51**:187–197.
- North M, Innes J, Zald H. 2007. Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions. *Canadian Journal of Forest Research* **37**:331–342.

- North M, Stine P, O'Hara K, Zielinski W, Stephens S. 2009. An ecosystem management strategy for Sierran mixed-conifer forests. Gen. Tech. Rep. PSW-GTR-220. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
- Odion DC, Moritz MA, DellaSala DA. 2010. Alternative community states maintained by fire in the Klamath Mountains, USA. *Journal of Ecology* **98**:96–105.
- Parks SA, Miller C, Abatzoglou JT, Holsinger LM, Parisien M-A, Dobrowski SZ. 2016. How will climate change affect wildland fire severity in the western US? *Environmental Research Letters* **11**:035002.
- Parks SA, Miller C, Parisien M-A, Holsinger LM, Dobrowski SZ, Abatzoglou J. 2015. Wildland fire deficit and surplus in the western United States, 1984–2012. *Ecosphere* **6**:1–13.
- Perry DA, Hessburg PF, Skinner CN, Spies TA, Stephens SL, Taylor AH, Franklin JF, McComb B, Riegel G. 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and Northern California. *Forest Ecology and Management* **262**:703–717.
- Pharis RP. 1966. Comparative drought resistance of five conifers and foliage moisture content as a viability index. *Ecology* **47**:211–221.
- Pierce DW, Kalansky JF, Cayan DR. 2018. Climate, drought, and sea level rise scenarios for the Fourth California Climate Assessment. California's Fourth Climate Change Assessment. Publication Number: CNRA-CEC-2018-006. California Energy Commission, Sacramento, CA.
- Powell JA, Logan JA. 2005. Insect seasonality: circle map analysis of temperature-driven life cycles. *Theoretical Population Biology* **67**:161–179.
- Raffa KF, Aukema BH, Bentz BJ, Carroll AL, Hicke JA, Turner MG, Romme WH. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *BioScience* **58**:501–517.
- Rapacciuolo G et al. 2014. Beyond a warming fingerprint: individualistic biogeographic responses to heterogeneous climate change in California. *Global Change Biology* **20**:2841–2855.
- Rauscher SA, Pal JS, Diffenbaugh NS, Benedetti MM. 2008. Future changes in snowmelt-driven runoff timing over the western US. *Geophysical Research Letters* **35**:L16703.
- Reilly MJ, Spies TA. 2016. Disturbance, tree mortality, and implications for contemporary regional forest change in the Pacific Northwest. *Forest Ecology and Management* **374**:102–110.
- Reilly MJ, Spies TA, Littell J, Butz R, Kim JB. 2018. Chapter 2: Climate, disturbance, and vulnerability to vegetation change in the Northwest Forest Plan Area. Pages 29–94 in T. A. Spies, P. A. Stine, R. Gravenmier, J. W. Long, and M. J. Reilly, editors. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Royce EB, Barbour MG. 2001. Mediterranean climate effects. II. Conifer growth phenology across a Sierra Nevada ecotone. *American Journal of Botany* **88**:919–932.
- Safford HD, Stevens JT. 2017. Natural Range of Variation (NRV) for yellow pine and mixed conifer forests in the Sierra Nevada, southern Cascades, and Modoc and Inyo National Forests, California, USA. Gen. Tech. Rep. PSW-GTR-256. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
- Safford HD, Van de Water KM. 2014. Using fire return interval departure (FRID) analysis to map spatial and temporal changes in fire frequency on national forest lands in California. Res. Pap. PSW-RP-266. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
- Scheller RM, Kretchun AM, Loudermilk EL, Hurteau MD, Weisberg PJ, Skinner C. 2018. Interactions among fuel management, species composition, bark beetles, and climate change and the potential effects on forests of the Lake Tahoe Basin. *Ecosystems* **21**:643–656.
- Schenck SM, Gifford EW. 1952. Karuk ethnobotany. University of California Press, Berkeley, CA.

- Schierenbeck KA. 2017. Population-level genetic variation and climate change in a biodiversity hotspot. *Annals of Botany* **119**:215–228.
- Schoettle AW, Sniezko RA. 2007. Proactive intervention to sustain high-elevation pine ecosystems threatened by white pine blister rust. *Journal of Forest Research* **12**:327–336.
- Schoettle AW, Sniezko RA, Kegley A, Burns KS. 2014. White pine blister rust resistance in limber pine: evidence for a major gene. *Phytopathology* **104**:163–173.
- Serra-Diaz JM, Franklin J, Dillon WW, Syphard AD, Davis FW, Meentemeyer RK. 2016. California forests show early indications of both range shifts and local persistence under climate change. *Global Ecology and Biogeography* **25**:164–175.
- Shatford JPA, Hibbs DE, Puettmann KJ. 2007. Conifer regeneration after forest fire in the Klamath-Siskiyou: how much, how soon? *Journal of Forestry* **105**:139–146.
- Skinner C, Abbott C, Fry D, Stephens S, Taylor A, Trouet V. 2009. Human and climatic influences on fire occurrence in California's North Coast range. *Fire Ecology* **5**:76–99.
- Skinner CN, Taylor AH. 2006. Southern Cascades bioregion. Pages 195–224 in N. G. Sugihara, J. W. van Wagtendonk, J. Fites-Kaufmann, K. E. Shaffer, and A. E. Thode, editors. *Fire in California's ecosystems*. University of California Press, Berkeley, CA.
- Skinner CN, Taylor AH, Agee JK. 2006. Klamath Mountains bioregion. Pages 170–194 in N. G. Sugihara, J. W. van Wagtendonk, J. Fites-Kaufmann, K. E. Shaffer, and A. E. Thode, editors. *Fire in California's ecosystems*. University of California Press, Berkeley, CA.
- Slack A, Kane J, Knapp E, Sherriff R. 2017. Contrasting impacts of climate and competition on large sugar pine growth and defense in a fire-excluded forest of the central Sierra Nevada. *Forests* **8**:244.
- Smith RS. 1996. Spread and intensification of blister rust in the range of sugar pine. Pages 112–118 in B. B. Kinloch Jr., M. Marosy, and M. E. Huddleston, editors. *Sugar pine: status, values, and roles in ecosystems*. Davis, CA, 1992 March 30–April 1. Publ. 3362. University of California, Division of Agriculture and Natural Resources, Davis, CA.
- Sniezko RA, Kegley AJ, Danchok R. 2008. White pine blister rust resistance in North American, Asian and European species - results from artificial inoculation trials in Oregon. *Annals of Forest Research* **51**:53–66.
- Sniezko RA, Samman S, Schlarbaum SE, Kriebel HB. 2004. Breeding and genetic resources of five-needle pines: growth, adaptability, and pest resistance. Proceedings RMRS-P-32. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Spies TA, Hemstrom MA, Youngblood A, Hummel S. 2006. Conserving old-growth forest diversity in disturbance-prone landscapes. *Conservation Biology* **20**:351–362.
- Steel ZL, Safford HD, Viers JH. 2015. The fire frequency-severity relationship and the legacy of fire suppression in California forests. *Ecosphere* **6**:1–23.
- Stephens SL, Collins BM, Fettig CJ, Finney MA, Hoffman CM, Knapp EE, North MP, Safford H, Wayman RB. 2018. Drought, tree mortality, and wildfire in forests adapted to frequent fire. *BioScience* **68**:77–88.
- Stephens SL, Martin RE, Clinton NE. 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *Forest Ecology and Management* **251**:205–216.
- Stephenson N. 1998. Actual evapotranspiration and deficit: biologically meaningful correlates of vegetation distribution across spatial scales. *Journal of Biogeography* **25**:855–870.
- Stewart IT, Cayan DR, Dettinger MD. 2004. Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. *Climatic Change* **62**:217–232.
- Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate* **18**:1136–1155.
- Stuart JD, Salazar LA. 2000. Fire history of white fir forests in the coastal mountains of northwestern California. *Northwest Science* **74**:280–285.

- Sturrock RN, Frankel SJ, Brown AV, Hennon PE, Kliejunas JT, Lewis KJ, Worrall JJ, Woods AJ. 2011. Climate change and forest diseases. *Plant Pathology* **60**:133–149.
- Syphard AD, Keeley JE, Pfaff AH, Ferschweiler K. 2017. Human presence diminishes the importance of climate in driving fire activity across the United States. *Proceedings of the National Academy of Sciences* **114**:13750–13755.
- Taylor AH, Skinner CN. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. *Ecological Applications* **13**:704–719.
- Taylor AH, Trouet V, Skinner CN, Stephens S. 2016. Socioecological transitions trigger fire regime shifts and modulate fire–climate interactions in the Sierra Nevada, USA, 1600–2015 CE. *Proceedings of the National Academy of Sciences* **113**:13684–13689.
- Thayer TC, Vander Wall SB. 2005. Interactions between Steller’s jays and yellow pine chipmunks over scatter-hoarded sugar pine seeds. *Journal of Animal Ecology* **74**:365–374.
- Thompson JR, Spies TA. 2010. Factors associated with crown damage following recurring mixed-severity wildfires and post-fire management in southwestern Oregon. *Landscape Ecology* **25**:775–789.
- Thorne JH, Boynton RM, Flint LE, Flint AL. 2015. The magnitude and spatial patterns of historical and future hydrologic change in California’s watersheds. *Ecosphere* **6**:1–30.
- Tomback DF, Achuff P. 2010. Blister rust and western forest biodiversity: ecology, values and outlook for white pines. *Forest Pathology* **40**:186–225.
- Van de Water KM, Safford HD. 2011. A summary of fire frequency estimates for California vegetation before Euro-American settlement. *Fire Ecology* **7**:26–58.
- van Mantgem PJ, Caprio AC, Stephenson NL, Das AJ. 2016. Does prescribed fire promote resistance to drought in low elevation forests of the Sierra Nevada, California, USA? *Fire Ecology* **12**:13–25.
- van Mantgem PJ, Nesmith JCB, Keifer M, Knapp EE, Flint A, Flint L. 2013. Climatic stress increases forest fire severity across the western United States. *Ecology Letters* **16**:1151–1156.
- van Mantgem PJ, Stephenson NL. 2007. Apparent climatically induced increase of tree mortality rates in a temperate forest. *Ecology Letters* **10**:909–916.
- van Mantgem PJ, Stephenson NL, Keifer M, Keeley J. 2004. Effects of an introduced pathogen and fire exclusion on the demography of sugar pine. *Ecological Applications* **14**:1590–1602.
- van Mantgem PJ et al. 2009. Widespread increase of tree mortality rates in the western United States. *Science* **323**:521–524.
- Vander Wall SB. 2003. Effects of seed size of wind-dispersed pines (*Pinus*) on secondary seed dispersal and the caching behavior of rodents. *Oikos* **100**:25–34.
- Vangestel C, Vázquez-Lobo A, Martínez-García PJ, Calic I, Wegrzyn JL, Neale DB. 2016. Patterns of neutral and adaptive genetic diversity across the natural range of sugar pine (*Pinus lambertiana* Dougl.). *Tree Genetics & Genomes* **12**:51.
- Vázquez-Lobo A et al. 2017. Finding loci associated to partial resistance to white pine blister rust in sugar pine (*Pinus lambertiana* Dougl.). *Tree Genetics & Genomes* **13**:108.
- Wahl ER, Zorita E, Trouet V, Taylor AH. 2019. Jet stream dynamics, hydroclimate, and fire in California from 1600 CE to present. *Proceedings of the National Academy of Sciences* **116**:5393–5398.
- Weed AS, Ayres MP, Hicke JA. 2013. Consequences of climate change for biotic disturbances in North American forests. *Ecological Monographs* **83**:441–470.
- Westerling AL. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**:20150178.
- Westerling AL. 2018. Wildfire simulations for California’s Fourth Climate Change Assessment: projecting changes in extreme wildfire events with a warming climate. California’s Fourth Climate Change Assessment. Publication Number: CCCA4-CEC-2018-014. California Energy Commission, Sacramento, CA.

- Westerling AL, Bryant BP, Preisler HK, Holmes TP, Hidalgo HG, Das T, Shrestha SR. 2011. Climate change and growth scenarios for California wildfire. *Climatic Change* **109**:445–463.
- Williams DW, Liebhold AM. 2002. Climate change and the outbreak ranges of two North American bark beetles. *Agricultural and Forest Entomology* **4**:87–99.
- Young D, Latimer A. 2017. Post-fire forest regeneration in a changing climate. JFSP PROJECT ID: 15-2-01-34. University of California, Davis.
- Young DJN, Stevens JT, Earles JM, Moore J, Ellis A, Jirka AL, Latimer AM. 2017. Long-term climate and competition explain forest mortality patterns under extreme drought. *Ecology Letters* **20**:78–86.
- Zald HSJ, Gray AN, North M, Kern RA. 2008. Initial tree regeneration responses to fire and thinning treatments in a Sierra Nevada mixed-conifer forest, USA. *Forest Ecology and Management* **256**:168–179.
- Zeglen S, Pronos J, Merler H. 2010. Silvicultural management of white pines in western North America. *Forest Pathology* **40**:347–368.

## Northern California Climate Adaptation Project: Vulnerability Assessment Methods and Application

---

### Defining Terms

**Exposure:** A measure of how much of a change in climate or climate-driven factors a resource is likely to experience (Glick et al. 2011).

**Sensitivity:** A measure of whether and how a resource is likely to be affected by a given change in climate or factors driven by climate (Glick et al. 2011).

**Adaptive Capacity:** The ability of a resource to accommodate or cope with climate change impacts with minimal disruption (Glick et al. 2011).

**Vulnerability:** A function of the sensitivity of a particular resource to climate changes, its exposure to those changes, and its capacity to adapt to those changes (IPCC 2007).

---

### Vulnerability Assessment Model

The vulnerability assessment model applied in this process was developed by EcoAdapt (EcoAdapt 2014a; EcoAdapt 2014b; Kershner 2014; Hutto et al. 2015; Gregg 2018),<sup>11</sup> and includes evaluations of relative vulnerability by local and regional stakeholders who have detailed knowledge about and/or expertise in the ecology, management, and threats to focal habitats, species groups, individual species, and the ecosystem services that these resources provide. Stakeholders evaluated vulnerability for each resource by discussing and answering a series of questions for sensitivity and adaptive capacity. Exposure was evaluated by EcoAdapt using projected future climate changes from the scientific literature. Each vulnerability component (i.e., sensitivity, adaptive capacity, and exposure) was divided into specific elements. For example, habitats included three elements for assessing sensitivity and six elements for adaptive capacity. Elements for each vulnerability component are described in more detail below.

In-person workshops were held in Eureka, Redding, and Upper Lake between May and October 2017. Participants self-selected habitat and species group/species breakout groups and evaluated the vulnerability of each resource. Participants were first asked to describe the habitat and/or to list the species to be considered in the evaluation of an overarching species group. Due to limitations in workshop time and participant expertise, multiple resources were not assessed during these engagements. Evaluations for remaining habitats, species groups, and species were completed by contacting resource experts.<sup>12</sup>

---

<sup>11</sup> Sensitivity and adaptive capacity elements were informed by Lawler 2010, Glick et al. 2011, and Manomet Center for Conservation Sciences 2012.

<sup>12</sup> Resources evaluated by experts included: coastal bluff/scrub habitats, coastal conifer hardwood forest, true fir forest, lakes/ponds, freshwater marshes, vernal pools, seeps/springs, native insect pollinators, native ungulates, salamanders, frogs, native mussels, marbled murrelet, and northwestern pond turtle.

Stakeholders assigned one of five rankings (High, Moderate-High, Moderate, Low-Moderate, or Low) for sensitivity and adaptive capacity. EcoAdapt assigned rankings for projected future climate exposure. Rankings for each component were then converted into scores (High-5, Moderate-High-4, Moderate-3, Low-Moderate-2, or Low-1), and the scores were averaged (mean) to generate an overall score. For example, scores for each element of habitat sensitivity were averaged to generate an overall habitat sensitivity score. Scores for exposure were weighted less than scores for sensitivity and adaptive capacity because the uncertainty about the magnitude and rate of future change is greater. Sensitivity, adaptive capacity, and exposure scores were combined into an overall vulnerability score calculated as:

$$\text{Vulnerability} = [(\text{Climate Exposure} * 0.5) \times \text{Sensitivity}] - \text{Adaptive Capacity}$$

Elements for each component of vulnerability were also assigned one of three confidence rankings (High, Moderate, or Low). Confidence rankings were converted into scores (High-3, Moderate-2, or Low-1) and the scores averaged (mean) to generate an overall confidence score. These approximate confidence levels were based on the Manomet Center for Conservation Sciences (2012) 3-category scale, which collapsed the 5-category scale developed by Moss and Schneider (2000) for the IPCC Third Assessment Report. The vulnerability assessment model applied here assesses the confidence associated with individual element rankings and, from these rankings, estimates the overall level of confidence for each component of vulnerability and then for overall vulnerability.

Stakeholders and decision-makers can consider the rankings and scores presented as measures of relative vulnerability and confidence to compare the level of vulnerability among the focal resources evaluated in this project. Elements that received lower confidence rankings indicate knowledge gaps that applied scientific research could help address.

### Vulnerability Assessment Model Elements

#### *Sensitivity & Exposure (Applies to Habitats, Species Groups, Species)*

- **Climate and Climate-Driven Factors:** e.g., air temperature, precipitation, freshwater temperature, soil moisture, snowpack, extreme events: drought, altered streamflows, etc.
- **Disturbance Regimes:** e.g., wildfire, flooding, drought, insect and disease outbreaks, wind
- **Future Climate Exposure:** e.g., consideration of projected future climate changes (e.g., temperature and precipitation) as well as climate-driven changes (e.g., altered fire regimes, altered water flow regimes, shifts in vegetation types)
- **Stressors Not Related to Climate:** e.g., tectonic and volcanic events; residential or commercial development; agriculture and/or aquaculture; roads, highways, trails; dams and water diversions; invasive and other problematic species; livestock grazing; fire suppression; timber harvest; mining; etc.

*Sensitivity & Exposure (Applies to Species Groups and Species)*

- **Dependencies:** e.g., dependencies on sensitive habitats, specific prey or forage species, and the timing of the appearance of these prey and forage species (concern for mismatch)

*Sensitivity & Exposure (Applies to Species ONLY)*

- **Life History:** e.g., species reproductive strategy, average length of time to reproductive maturity

*Adaptive Capacity (Applies to Habitats, Species Groups, Species)*

- **Extent, Integrity, and Continuity/Connectivity:** e.g., resources that are widespread vs. limited, structural and functional integrity (e.g., degraded or pristine) of a habitat or health and functional integrity of species (e.g., endangered), isolated vs. continuous distribution
- **Landscape Permeability:** e.g., barriers to dispersal and/or continuity (e.g., land-use conversion, energy production, roads, timber harvest, etc.)
- **Resistance and Recovery:** e.g., *resistance* refers to the stasis of a resource in the face of change, *recovery* refers to the ability to “bounce back” more quickly from the impact of stressors once they occur
- **Management Potential:** e.g., ability to alter the adaptive capacity and resilience of a resource to climatic and non-climate stressors (societal value, ability to alleviate impacts, capacity to cope with impacts)
- **Ecosystem Services:** e.g., provisioning, regulating, supporting, and/or cultural services that a resource produces for human well-being

*Adaptive Capacity (Applies to Habitats ONLY)*

- **Habitat Diversity:** e.g., diversity of physical/topographical characteristics, component native species and functional groups

*Adaptive Capacity (Applies to Species Groups, Species)*

- **Dispersal Ability:** i.e., ability of a species to shift its distribution across the landscape as the climate changes
- **Intraspecific/Life History Diversity:** e.g., life history diversity, genetic diversity, phenotypic and behavioral plasticity

## Literature Cited

- EcoAdapt. 2014a. A climate change vulnerability assessment for aquatic resources in the Tongass National Forest. EcoAdapt, Bainbridge Island, WA. 124 pp.
- EcoAdapt. 2014b. A climate change vulnerability assessment for resources of Nez Perce-Clearwater National Forests. Version 3.0. EcoAdapt, Bainbridge Island, WA. 398 pp.
- Glick P, Stein BA, Edelson NA. 2011. Scanning the conservation horizon: A guide to climate change vulnerability assessment. National Wildlife Federation, Washington, D.C.
- Gregg RM, editor. 2018. Hawaiian Islands climate vulnerability and adaptation synthesis. EcoAdapt, Bainbridge Island, WA. 284 pp.

- Hutto SV, Higgason KD, Kershner JM, Reynier WA, Gregg DS. 2015. Climate change vulnerability assessment for the north-central California coast and ocean. Marine Sanctuaries Conservation Series ONMS-15-02. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 473 pp.
- Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Pages 617–652 in M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, editors. Cambridge University Press, Cambridge, UK.
- Kershner JM, editor. 2014. A climate change vulnerability assessment for focal resources of the Sierra Nevada. Version 1.0. EcoAdapt, Bainbridge Island, WA. 418 pp.
- Lawler J. 2010. Pacific Northwest Climate Change Vulnerability Assessment. From <http://climatechangesensitivity.org>
- Manomet Center for Conservation Sciences and National Wildlife Federation. 2012. The vulnerabilities of fish and wildlife habitats in the Northeast to climate change. A report to the Northeastern Association of Fish and Wildlife Agencies and the North Atlantic Landscape Conservation Cooperative. Manomet Center for Conservation Sciences, Plymouth, MA.
- Moss R, Schneider S. 2000. Towards consistent assessment and reporting of uncertainties in the IPCC TAR. In R. Pachauri and T. Taniguchi, editors. *Cross-Cutting Issues in the IPCC Third Assessment Report*. Global Industrial and Social Progress Research Institute (for IPCC), Tokyo.