Endemic Habitats

Northern California Climate Change Vulnerability Assessment Synthesis

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for endemic habitats 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 (Bureau of Land Management), Julie Nelson (U.S. Forest Service), and Eric Ritter (Bureau of Land Management). Vulnerability scores were provided by Eureka and Redding workshop participants.

Table of Contents

Habitat Description

Within the context of this assessment, endemic habitats are considered geologic islands influenced by extreme abiotic factors relating to the soil/substrate (i.e., edaphic conditions), which can include shallow substrate depth, macronutrient deficiency, and high micronutrient or heavy metal toxicity. Examples of edaphic endemic habitats that occur in northwestern California include rock outcrops, cliffs and talus slopes; serpentine; hydro-thermally-altered rocks; saline-alkaline soils; and limestone and other carbonate rocks. In addition to surface edaphic endemic habitats, this vulnerability assessment also considers subterranean rock shelters, limestone caves, and lava tubes in the northwestern California region. Because they are typically surrounded by much larger areas of normal substrates, these extreme geologic and edaphic habitats are analogous to isolated habitat islands (Kruckeberg 1986, 1991; Rajakaruna 2004). Endemic ecosystems provide habitat for hundreds of plant, lichen, invertebrate, and bat species that have evolved in isolation under extreme site and/or microclimate conditions, resulting in many rare and/or endemic species (including single-site endemics) and unique species assemblages (Rajakaruna 2004; Safford et al. 2005; Kruckeberg 2006; O'Dell & Rajakaruna 2011; Yost et al. 2012; Harrison 2013; Rajakaruna et al. 2014).

Rock outcrops, cliffs, and talus slopes
Exposed bedrock outcrops, talus slopes, barrens, and cliffs are scattered across the region, often at higher elevations (Vuln. Assessment Workshop, pers. comm., 2017). These landforms occur in diverse geologic settings, with slopes that range from vertical to flat (Parisi 1988; Rundel & Millar 2016; Vuln. Assessment Workshop, pers. comm., 2017). Although the chemical composition of these habitats may not be unusual, frequent substrate movement and poor water-holding capacity results in low vegetation cover (Vuln. Assessment Reviewer, pers. comm., 2019). For example, Castle Crags bellflower (*Campanula shetleri*) and Castle Crags ivesia (*Ivesia longebracteata*) only occur in high granitic spires and cliffs near the town of Castella in Shasta County, where few other plants can survive (Vuln. Assessment Reviewer, pers. comm., 2019). Because soil development in these environments is very slow, biological communities often include lichens on exposed surfaces and isolated vascular plants within protected microenvironments (Körner 2007; Aho et al. 2014). Many talus slopes are relict landforms, but some remain highly mobile (Luckman 2013). Cliffs may also occur naturally or along human-created road cuts (Vuln. Assessment Workshop, pers. comm., 2017).

Serpentine
Ultramafic rocks (i.e., serpentine) include serpentinite and peridotite rocks, which weather at the Earth surface to form soils with distinctive chemical and physical properties (Kruckeberg 1984; Alexander et al. 2007). The resulting soils have extreme deficiencies of macronutrients required by plants (e.g., nitrogen, phosphorus, potassium, calcium) and toxic concentrations of magnesium and heavy metals such as nickel (Kruckeberg 1984; Alexander et al. 2007). These properties restrict plant establishment and growth, so serpentine vegetation is generally sparse (Kruckeberg 1984; Alexander et al. 2007). Serpentine communities generally include many endemic plant species that are poor competitors in more productive soils, but have specialized physiological adaptations to cope with extreme calcium deficiency and magnesium toxicity (Safford et al. 2005; Alexander et al. 2007; Harrison 2013). In northern California, endemic serpentine habitats occur at a range of elevations in the Klamath Mountains and North Coast Ranges south through the Berryessa Snow Mountain National Monument (Kruckeberg 1984; Alexander et al. 2007). They are associated with several important ultramafic geologic features including the Josephine ophiolite (Harper 1984), the Rattlesnake Creek terrane (Wright & Wyld 1994), and the Trinity Ultramafic Sheet (Alexander et al. 2007).

Hydrothermally-altered rocks

Hydrothermally-altered substrates occur at hydrothermal steam vents and hot springs (O'Dell 2014) and contain an abundance of elemental sulfur and sulfide minerals that undergo microbally-mediated oxidation upon exposure to the atmosphere (Billings 1950; Salisbury 1954, 1964). This results in substrate acidification and the generation of sulfuric acid, exacerbating macronutrient deficiencies and heavy metal toxicity (Billings 1950; Salisbury 1954, 1964). The sulfuric acid and heavy metals can also affect perennial water sources as acid mine drainage (AMD; O'Dell 2014), which in northwestern California primarily occurs within the Shasta copper-zinc district (e.g. Iron Mountain northwest of Redding; Kinkel et al. 1956). Hydrothermally-altered habitats also occur in several other isolated mining complexes in the region (e.g. Grey Eagle Mine north of Happy Camp; Vuln. Assessment Reviewer, pers. comm., 2019). Some plant species, such as *Vaccinium shastense* subsp. *shastense*, have become edaphic endemic specialists of hydrothermally-altered rocks of the region (Nelson & Lindstrand 2015).

Saline-alkaline seeps and sinks

Saline substrates have a high concentration of salt, which impairs plant growth by making it difficult for plants to draw water from the soil and inhibiting metabolic processes (Saslis-Lagoudakis et al. 2014). Saline substrates are frequently associated with alkaline pH, which decreases the soil availability of nutrients (Saslis-Lagoudakis et al. 2014). Some plant families (e.g., Chenopodiaceae) and particular genera in other plant families (e.g., *Puccinellia* in Poaceae) have specialized physiological adaptations to cope with high salinity (Saslis-Lagoudakis et al. 2014). For instance, saltgrass (*Distichlis spicata*) is a common indicator species from small saline springs and seeps (Vuln. Assessment Reviewer, pers. comm., 2020). The local endemic *Puccinellia howellii* is known from only one location, the 1-acre saline Crystal Springs complex within Whiskeytown National Recreation Area in the Klamath Mountains (Cooper & Wolf 2007). Other saline-alkaline spring/sink complexes are located between the cities of Weed and Yreka in Siskiyou County, which are ecologically most similar to saline-alkaline sinks of the Great Basin. Saline sites also occur in the geothermal region around Clear Lake (Vuln. Assessment Reviewers, pers. comm., 2019 and 2020). One species, *Calochortus monanthus*, was endemic to the saline-alkaline seep and wetland complexes in this area, but has not been seen in 100 years and is now presumed extinct (Rejmánek 2018; Vuln. Assessment Reviewer, pers. comm., 2019).

Limestone, marble, dolomite, and other carbonate rocks

Carbonate substrates are comprised of the skeletal remains of marine organisms (O'Dell 2014), and result in the opposite extreme chemical condition of serpentine with very high calcium to magnesium ratio (Kruckeberg 2006). Karst terrain occurs where these soluble rocks are dissolved by naturally acidic surface or groundwater, creating landscapes with complex underground systems that include caves, sinkholes, and large aquifers (Winter et al. 1998). Limestone and other soluble carbonate rocks (e.g., dolomite, marble, gypsum) are less prevalent in northern California than are volcanic, metasedimentary, sedimentary, granitic, and ultramafic rocks (Vuln. Assessment Reviewer, pers. comm., 2019). Although isolated chunks of limestone occur throughout the region, they only occur in more extensive contiguous outcrops within the Hosselkus and McCloud Formations in Shasta and Siskiyou Counties (Vuln.

Assessment Reviewer, pers. comm., 2019). These formations are home to a suite of rare, endemic plant species (Harrison 2013), including Shasta snakeroot (*Ageratina shastensis*), Shasta limestone monkeyflower (*Erythranthe taylori*), Shasta snow-wreath (*Neviusia cliftonii*), and Marble Mountain catchfly (*Silene marmorensis*; O'Dell 2014).

Subsurface ecosystems – caves, rock shelters, and lava tubes
Northern California contains caves formed by the dissolution of soluble rock (i.e., solution caves, which often occur within karst landscapes), caves and rock shelters that are formed by rock fall/talus features, and lava tubes (Winter et al. 1998; Vuln. Assessment Workshop, pers. comm., 2017). Caves contain distinct zones with differing environmental conditions and biotic communities: the entrance zone, twilight zone, and dark zone (Elliott et al. 2017). Generally, caves are very steady environments, with light, humidity, airflow, and air chemistry variability declining with increasing distance into the cave (Badino 2010; Vuln. Assessment Workshop, pers. comm., 2017). Caves are scattered throughout northwestern California, and are particularly common in the Klamath and Shasta-Trinity National Forests (Elliott et al. 2017). Larger groups of caves occur in the Marble Mountains and in the McCloud Limestone formation in the Shasta Lake region (Elliott et al. 2017), including Samwell Cave, which is located within karst topography near Shasta Lake (Vuln. Assessment Reviewer, pers. comm., 2019). Abandoned mines may also function as caves by providing habitat for cave-dwelling species (Elliott et al. 2017), and abandoned metal mines represent extreme edaphic habitats for plants (O'Dell 2014).

The physical characteristics of rock shelters are more variable depending on the characteristics of surrounding rocks, and they typically do not have "dark zones" (Vuln. Assessment Reviewer, pers. comm., 2019). Fissures and cracks above the rock shelter may allow trapped moisture to make its way down onto the roof of the shelter, depositing salts (Vuln. Assessment Reviewer, pers. comm., 2019). Many rock shelters and some caves have aprons/cones of rock fragments in front of them, sometimes including cultural or anthropic deposits (Vuln. Assessment Reviewer, pers. comm., 2019).

Lava tubes are volcanic features that form when the outer surface of a lava flow cools and hardens while the molten lava within continues to flow and eventually drains out of the hardened tube (Kilburn 2000). Volcanic terrain, such as occurs in Shasta and Siskiyou Counties, is associated with variable and complex substrates that can include exposed lava flows, scab rock, and tumuli (pressure ridges; Vuln. Assessment Reviewer, pers. comm., 2019). A very large-diameter lava tube named Pluto's Cave occurs in Shasta County (Vuln. Assessment Reviewer, pers. comm., 2019). However, most lava tubes in the state are clustered outside of the study area in northeastern California (Elliott et al. 2017).

Executive Summary

The relative vulnerability of surface endemic habitats in northern California was evaluated as moderate by regional experts due to moderate-high sensitivity to climate and non-climate stressors, moderate exposure to projected future climate changes, and low-moderate adaptive capacity. Subsurface endemic habitats were evaluated as having moderate vulnerability due to low-moderate sensitivity, moderate-high future exposure, and low-moderate adaptive capacity.

Rank (Confidence)	**Surface Endemic Habitats**	**Subsurface Endemic Habitats**
Sensitivity	Moderate-High (High)	Low-Moderate (High)
Exposure	Moderate (Low)	Moderate-High (Moderate)
Adaptive Capacity	Low-Moderate (Moderate)	Low-Moderate (High)
Collective Vulnerability	**Moderate (Moderate)**	**Moderate (Moderate)**

Sensitivity & Exposure Summary	
	Climate and climate-driven factors: • Air temperature, heat waves, precipitation amount and timing, soil moisture, drought, snowpack amount, timing of snowmelt/runoff *Disturbance regimes*: • Wildfire, flooding *Non-climate stressors*: • Invasive species, fire suppression, livestock grazing

Endemic habitats are sensitive to climate factors that alter surface energy (e.g., air temperature, heat waves) and water supply (precipitation, soil moisture, drought, snowpack, timing of snowmelt and runoff) in endemic ecosystems. Changes in these factors may increase physiological stress in plants, altering competitive dynamics within species assemblages. Climate changes and disturbances (e.g., wildfire, flooding) can also result in physical changes such as soil erosion in endemic habitats, as well as altered microclimate conditions following changes in physical conditions or vegetation structure (e.g., type conversion of forest to chaparral following wildfire). Non-climate stressors can further exacerbate the negative impacts of climate change. For instance, increased competition from invasive species may contribute to the loss of rare plants and invertebrates, particularly where systems have already been altered or degraded (e.g., increased nutrient inputs in serpentine habitats).

Adaptive Capacity Summary	*Factors that enhance adaptive capacity*: + Support highly specialized biota adapted to unique environmental conditions + Somewhat buffered from the impacts of human disturbance and invasive species colonization in high-elevation and/or remote locations + Caves and talus habitats support relatively stable thermal regimes that are buffered from the impacts of rapid climate change *Factors that undermine adaptive capacity*: – Rock-dominated habitat cannot move in response to changing climate, and associated biota will likely need to adapt or migrate to new habitat to survive, if possible – Human visitation and use of caves can increase degradation and reduce adaptive capacity – Isolated, fragmented habitats; difficult for wildlife and plants to move between habitat islands

The high topographic and geologic complexity of the region have contributed to high rates of genetic divergence and speciation within endemic habitats, allowing specialized species to survive in areas where competition from habitat generalists is low. Endemic habitats in northern California are typically isolated, which limits opportunities for biotic migration and dispersal in respose to climate and non-climate stressors. Endemic habitats are valued for their biological diversity and recreation potential, and many rare endemic plant species are protected by state and federal legislation. Management of these habitats is likely to focus on the identification and protection of refugia at varying spatial scales, as well as the protection of endemic habitats and rare species from land-use change and disturbance.

Sensitivity and Exposure

Surface endemic habitats were evaluated by regional experts as having moderate-high overall sensitivity (high confidence in evaluation) and moderate overall future exposure (low confidence) to climate and climate-driven factors, changes in disturbance regimes, and non-climate stressors. Subsurface endemic habitats were evaluated as having low-moderate overall sensitivity (high confidence) and moderate-high future exposure (moderate confidence).

Predicting the future persistence and distribution of edaphic endemic plants is difficult due to their association with unique geologic and topographic features. Changes in climatic conditions may impact the niche of endemic plant species, and the ability of a given species to migrate to newly suitable areas is dependent on both plant dispersal ability and the extent and continuity of appropriate edaphic conditions required for that species (Damschen et al. 2012; Cunze et al. 2013).

Sensitivity and future exposure to climate and climate-driven factors

Regional experts evaluated surface endemic habitats as having moderate-high sensitivity to climate and climate-driven factors (moderate confidence in evaluation), with an overall moderate-high future exposure to these factors within the study region (moderate confidence). Subsurface endemic habitats were evaluated as having low sensitivity to climate and climate-driven factors (high confidence) and moderate-high future exposure to these factors (moderate confidence). Key climatic factors that affect endemic habitats include air temperature, heat waves, precipitation amount and timing, soil moisture, drought, snowpack amount, and timing of snowmelt and runoff (see Table 1).[1]

Table 1. Current and projected future trends in key climate and climate-driven factors within the study region, as well as their potential impacts on endemic habitats.

<table>
<tr><th colspan="2">Air temperature and heat waves[2]</th></tr>
<tr><td>Historical & current trends:
• 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)
  ○ No seasonal temperature trends available
• Increase in the frequency of humid nighttime events over the past several decades (Gershunov & Guirguis 2012)
• High interannual and interdecadal variability in heat waves (Gershunov & Guirguis 2012)</td><td>Projected future trends:
• 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 ecoregions (Flint et al. 2013; Flint & Flint 2014)
  ○ 1.9–5.8°C (3.4–10.4°F) increase in average winter minimum temperatures
  ○ 2.2–6.7°C (4.0–12.1°F) increase in average summer maximum temperatures
• Increased heat waves, with the greatest increase in humid nighttime heat waves and in coastal areas (Gershunov & Guirguis 2012)
• 2–6°C (3.6–10.8°F) increase in the temperature of the hottest day of the year by 2100 (Pierce et al. 2018)</td></tr>
<tr><td colspan="2">Summary of Potential Impacts on Species Group
• Increased heat and drought may cause local extinctions of endemic plant species due to discontinuity (island-like distribution) of habitat (Ackerly 2003; Harrison & Noss 2017), and may already be occurring in lower-elevation Sedum species (Zika et al. 2018). Dispersal and migration from south-facing to north-facing slopes may allow some plant species to persist in topographic microrefugia and/or track their microclimate across the landscape (Damschen et al. 2010), depending on dispersal ability and edaphic habitat extent and connectivity (Loarie et al. 2008; Damschen et al. 2012; Anacker et al. 2013).</td></tr>
</table>

[1] Climate and climate-driven factors presented are those ranked as having a moderate or higher impact on one or more of the habitats considered in this group; additional climate and climate-driven factors that may influence subsurface habitats to a lesser degree include streamflow and water temperature.
[2] Trends in climate factors and natural disturbance regimes presented in this and subsequent summary tables are not habitat-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.

- Less frequent freeze/thaw cycles may benefit cliff-resident plants, mosses, lichens, and invertebrates by providing more stable environmental conditions (Vuln. Assessment Workshop, pers. comm., 2017).
- Multiple studies have found that plants and invertebrates with narrow thermal tolerances are more vulnerable to climate change, while those that can withstand a wide range of temperatures are more likely to continue to experience conditions that remain within their thermal limits (Anacker et al. 2013; Sánchez-Fernández et al. 2016).
- In general, mobile species are less sensitive to extreme heat events than plants and sedentary wildlife species because they are able to seek out thermal refugia (Vuln. Assessment Workshop, pers. comm., 2017).
- In subsurface habitats such as caves, annual and interannual temperature variability can be very low (Badino 2004, 2010). Due to the heat sink effect of rock (i.e., thermal inertia), cave interiors are likely to warm more slowly (by up to several decades) and steadily than surface habitats (Badino 2004). Cave entrances and shallow caves/rock shelters are likely to experience more rapid changes (Badino 2004).
- Other more general impacts of warming air temperatures include enhanced extent and rate of spread of invasive species in California (Wolf et al. 2016) and increased risk of wildfire due to reductions in fuel moisture (Abatzoglou & Williams 2016; Gergel et al. 2017).

Precipitation amount/timing, soil moisture, and drought	
Historical & current trends: • 7.2–9.4 cm (2.8–3.7 in) increase in mean annual precipitation between 1900 and 2009 for the Northwestern California and Southern Cascade ecoregions (Rapacciuolo et al. 2014) • No published studies are available evaluating temporal soil moisture trends in the study region • Drought years have occurred twice as often over the last two decades compared to the previous century (Diffenbaugh et al. 2015) • 2012–2014 drought set records for lowest precipitation, highest temperatures, and most extreme drought indicators on record (Griffin & Anchukaitis 2014; Diffenbaugh et al. 2015)	*Projected future trends:* • 20% decrease to 34% increase in mean annual precipitation by 2100 (compared to 1951–1980) for the North Coast, Northern Coast Range, Northern Interior Coast Range, Klamath Mountain, and Southern Cascade ecoregions (Flint et al. 2013; Flint & Flint 2014)[3] • Seasonal changes are projected to be more significant as the wet season becomes wetter and shorter (i.e., later onset of fall rains and earlier onset of summer drought) and the dry season becomes drier and longer (Pierce et al. 2018; Swain et al. 2018) • Overall, interannual variability is expected to increase (Pierce et al. 2018; Swain et al. 2018) • Decreased top-level soil moisture is likely even if precipitation increases due to temperature-related changes in evaporative demand (Pierce et al. 2018) • Drought years are twice as likely to occur over the next several decades due to increased co-occurrence of dry years with very warm years (Cook et al. 2015)

[3] Projections for changes in annual and seasonal precipitation by ecoregion can be found in the full climate impacts table (https://bit.ly/2LHgZaG).

	• 80% chance of multi-decadal drought by 2100 under a high-emissions scenario (Cook et al. 2015) • 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)

Summary of Potential Impacts on Species Group

- Soil texture and depth strongly influence water storage and soil moisture availability, and play a role in determining the distribution of endemic plant species. As a result, plant community composition within edaphic endemic habitats often varies along moisture gradients associated with differences in physical soil/substrate properties (Yost et al. 2012; Aho et al. 2014; Rossington et al. 2018).
    - Substrates with very shallow soils (e.g., rock outcrops) dry out quickly because they are unable to store water for longer periods, resulting in more variable moisture availability that is closely tied to precipitation timing (Vuln. Assessment Workshop, pers. comm., 2017). However, rock outcrops, cliffs, rock shelters, and talus slopes can contain pockets of sediment, and water can collect in fissures and cracks (Vuln. Assessment Reviewer, pers. comm., 2019). Soil moisture may also be higher in shaded microsites (e.g., under large blocks on talus slopes) where evaporation is reduced (Pérez 1998).
- Changes in precipitation timing and amount are likely to impact the reproduction of edaphic specialists and could be associated with shifts in species composition towards more drought-tolerant species (Aho et al. 2014; Rossington et al. 2018; Zika et al. 2018). For instance, drier conditions may benefit succulents by giving them a competitive advantage over other species (Vuln. Assessment Workshop, pers. comm., 2017).
    - However, the high prevalence of stress-tolerant functional traits in plant communities adapted to harsh edaphic conditions (Fernandez-Going et al. 2012; Fernandez-Going & Harrison 2013) may reduce their sensitivity to drier conditions and increased drought compared to plant communities on more productive soils (Harrison et al. 2015a, 2015b). Nevertheless, extreme drought conditions may exceed critical stress thresholds for endemic habitats, resulting in declines in species richness and diversity (Damschen et al. 2010; Harrison et al. 2015b; Copeland et al. 2016).
- Greater precipitation variability may increase the risk of invasion by non-native species. However, serpentine plant communities are generally more resistant to precipitation-driven changes in exotic species establishment compared to non-serpentine communities because nutrient limitations are the primary limiting factor rather than precipitation (Fernandez-Going et al. 2012; Eskelinen & Harrison 2013; Fernandez-Going & Harrison 2013).
- Plants and invertebrates at cave mouths and organisms associated with shallow caves and rock shelters are likely more sensitive to changes in moisture, humidity, and drought compared to those that live within deeper environments (Vuln. Assessment Workshop, pers. comm., 2017).
- In general, species with restricted dispersal ability are likely to be more sensitive to changes in temperature than mobile species because they are less able to shift their range in response to changing climatic conditions (i.e., due to lack of connectivity between isolated habitat patches) and/or seek out refugia during extreme events (Vuln. Assessment Workshop, pers. comm., 2017).
- Decreased rainfall and drought reduces groundwater recharge and may result in decreased spring discharge or total drying of springs (Vuln. Assessment Reviewer, pers. comm., 2019).

Snowpack amount and timing of snowmelt and runoff	
Historical & current trends: • 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) • 15–40-day shift towards earlier date of 90% snowmelt across the western U.S. since 1915 (Hamlet et al. 2005) • 10–30-day shift towards earlier timing of snowmelt-driven runoff across the western U.S. since 1948 (Stewart et al. 2005)	*Projected future trends:* • Decreases in April 1 SWE by 2100 (compared to 1951–1980; Flint et al. 2013; Flint & Flint 2014): ○ 86–99% decrease on the North Coast ○ 82–99% decrease in the Northern Coast Range ○ 99–100% decrease in the Northern Interior Coast Range ○ 72–94% decrease in the Klamath Mountains ○ 61–89% decrease in the Southern Cascades • 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)
Summary of Potential Impacts on Species Group • Endemic habitats at high elevations are likely to be impacted by declines in snowpack, which provide a major moisture source in semi-arid environments (Bishop 2010). Snowpack declines are likely to be associated with reduced growth and reproduction and possible range declines in species impacted by reduced moisture availability (CDFW 2018; Zika et al. 2018). ○ For instance, Lassics lupine (*Lupinus constancei*), which exists only on high-elevation serpentine soils in Humboldt and Trinity Counties, experienced a significant decline in 2015 (CDFW 2018), likely due to negligible winter snowpack during the winters of 2013-2014 and 2014-2015, in combination with historic drought and fire (CDFW 2018). • The presence of snow insulates plants in the winter, providing protection from wind desiccation and extreme cold (Bishop 2010). Thus, snowpack reductions may increase plant mortality or injury (Bishop 2010).	

Sensitivity and future exposure to changes in natural disturbance regimes

Regional experts evaluated endemic habitats as having moderate-high sensitivity to changes in natural disturbance regimes (high confidence in evaluation for surface habitats, moderate confidence for subsurface habitats). Surface endemic habitats were evaluated as having an overall moderate future exposure to these stressors within the study region (moderate confidence), while subsurface habitats were evaluated as having an overall moderate-high future exposure to these stressors (moderate confidence). Key disturbance regimes that affect endemic habitats are wildfire and flooding (see Table 2).[4]

[4] All disturbance regimes presented were ranked as having a moderate or higher impact on one or more of the habitats considered in this group. Earthquakes, volcanic activity, and landslides can also act as disturbances in these habitats.

Table 2. Current and projected future trends in natural disturbance regimes, as well as potential impacts on endemic habitats.

Wildfire	

Historical & current trends:
• 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 & Van de Water 2014)
• 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)
• Changes in large fires (over 400 ha) in the inland northern California/Sierra Nevada region since the 1970s (Westerling 2016):
  ○ 184–274% increase in frequency
  ○ 270–492% increase in total area burned
  ○ 215% increase in length of the fire season
• 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)
• No significant trends in the average areal proportion of high-severity fire were documented in northwestern CA from 1984–2008 (Miller et al. 2012; Parks et al. 2015; Law & Waring 2015; Keyser & Westerling 2017)
  ○ The relatively short period of record for fire severity data may obscure long-term trends
  ○ To date, there are no peer-reviewed studies on temporal trends in northern California fire severity that include data from the last ten years
	Projected future trends:
	• State-wide, up to 77% increase in mean annual area burned and 50% increase in the frequency of extremely large fires (>10,000 ha) by 2100 (Westerling 2018)
	  ○ Greatest increases in burned area (up to 400%) occur in montane forested areas in northern California (Westerling et al. 2011; Westerling 2018)
	  ○ Less significant increases or possible decrease along the North Coast (Westerling et al. 2011)
	• Little projected change in fire severity in northwestern California by 2050 in models based solely on historical fire-climate relationships (Parks et al. 2016)
	  ○ 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)
	• The majority of impacts to natural and human ecosystems come from extreme fire events (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)
	  ○ Generally, these patterns are not well-represented in studies that evaluate indices of mean fire size, intensity/severity, etc.

Summary of Potential Impacts on Species Group • Fire regimes in endemic habitats are tied to those of the surrounding areas (Vuln. Assessment Workshop, pers. comm., 2017), but serpentine soils have a strong effect on vegetation community response to fire (Harrison et al. 2003; Safford & Harrison 2004, 2008). Generally, post-fire recovery on serpentine sites is slower compared to non-serpentine sites, likely because plant recruitment and growth is limited by nutrient availability rather than space and light as is often the case in surrounding areas (Harrison et al. 2003; Safford & Harrison 2004, 2008). In serpentine chaparral	

communities, a more open habitat structure is also tied to reduced fire frequency and intensity (Safford & Harrison 2004; Anacker et al. 2011).

- Vegetation structure change (e.g., conversion of forest to chaparral) alters microclimates on the ground, resulting in changes to understory communities (Vuln. Assessment Reviewer, pers. comm., 2019).
- Rock outcrops and talus slopes can act as firebreaks, limiting fire spread within forested areas (Vuln. Assessment Workshop, pers. comm., 2017). However, extreme heat, ash deposition, and smoke can impact vascular plants, lichens, mosses, and soil organisms within endemic habitats, particularly during high-intensity fires (Vuln. Assessment Workshop, pers. comm., 2017).
- Wildfires burn vegetation at the mouth of caves and rock shelters, and may affect fauna that live at the entrance. Additionally, smoke can smudge cave/rock shelter interiors (Vuln. Assessment Workshop, pers. comm., 2017). The loss of surface vegetation can alter erosion and mineral/salt deposition in rock shelters (Vuln. Assessment Reviewer, pers. comm., 2019), while the loss of vegetation at the mouth of caves may expose the interior to human use and degradation (Vuln. Assessment Workshop, pers. comm., 2017).

Flooding	
Historical & current trends: • No published studies are available evaluating temporal flooding trends in the study region	*Historical & current trends:* • More frequent/severe winter flooding due to an increase in extreme precipitation events (Dettinger 2011; AghaKouchak et al. 2018; Swain et al. 2018; Grantham et al. 2018) • State-wide, 200-year floods are expected to increase in frequency by 300–400%, becoming 50-year floods (Swain et al. 2018)

Summary of Potential Impacts on Species Group

- Cave systems with direct hydrological connections to the surface may be subject to flooding during extreme precipitation events (Groves & Meiman 2005; Lee et al. 2012), particularly those that occur at lower elevations, along streams, and in canyon bottoms (Vuln. Assessment Workshop, pers. comm., 2017).
- Changes in the frequency and/or magnitude of flooding may alter patterns of erosion and sediment deposition (Vuln. Assessment Workshop, pers. comm., 2017), and can increase the susceptibility of cave-dwelling species to invasive species or pathogens introduced by floodwaters (Lee et al. 2012).
- Flooding can also alter hydrology in serpentine wetlands, potentially creating temporary hydrological connections with other aquatic systems through groundwater movement or surface flow (Vuln. Assessment Workshop, pers. comm., 2017)

Sensitivity and current exposure to non-climate stressors

Regional experts evaluated surface endemic habitats as having moderate sensitivity to non-climate stressors (high confidence in evaluation), while subsurface habitats were evaluated as having low-moderate sensitivity (moderate confidence). Both surface and subsurface endemic habitats were evaluated as having an overall low-moderate current exposure to these stressors within the study region (moderate confidence for surface habitats, high confidence for subsurface habitats). Key non-climate stressors that affect endemic habitats include invasive species, fire suppression, and livestock grazing (see Table 3).[5]

Table 3. Key non-climate stressors that affect the overall sensitivity of endemic habitats to climate change.

Invasive species

Summary of Potential Impacts on Species Group
• Yellow star thistle (*Centaurea solstitialis*), cheatgrass (*Bromus tectorum*), and other invasive grasses and forbs are among the most common invasive species in the region (Pitcairn et al. 2006; Brooks et al. 2016), particularly in disturbed areas (e.g., roadsides, clear-cuts, burned areas; Xiao et al. 2016). In general, invasion has the potential to alter ecosystems by displacing native plants, reducing wildlife habitat, driving more frequent fires due to greater fuel availability/continuity, altering soil chemistry, and impacting nutrient cycling and other ecosystem processes (Vitousek et al. 1997; Dukes & Mooney 2004; Brooks et al. 2016).
• Rock outcrops, cliffs, and talus slopes are vulnerable to invasive annual grasses and forbs (Vuln. Assessment Reviewer, pers. comm., 2017). For instance, yellow star thistle is a well-established invader of limestone rock outcrops at moderate elevations in the eastern Klamath Range around Shasta Lake (Vuln. Assessment Reviewer, pers. comm., 2019).
• Serpentine grasslands are naturally resistant to invasion due to their low nutrient availability. However, the addition of nitrogen (i.e., from industrial and vehicular emissions) allows exotic grasses and forbs to invade and establish dominance in low-nutrient soils, displacing native plants and pollinators (Huenneke et al. 1990; Weiss 1999; Vallano et al. 2012; Eskelinen & Harrison 2013).
  ○ Nitrogen deposition may also exacerbate the impacts of changing precipitation regimes by enhancing exotic species establishment in serpentine areas (Eskelinen & Harrison 2013).
• Endemic habitats that occur in subalpine and alpine zones, such as talus slopes and rock outcrops, are also relatively resistant to invasion due to the short growing season (Körner 2003) as well as abiotic limitations such as low organic soil availability and/or a highly mobile substrate (Pauchard et al. 2009; Kulonen et al. 2017). Warmer temperatures, longer snow-free periods, and more frequent disturbances may allow upslope expansion of non-native species that were historically limited by harsh climatic conditions (Pauchard et al. 2009; Rundel & Keeley 2016; Lembrechts et al. 2018).
  ○ Exotic invertebrates and pathogens (e.g., white nose syndrome, caused by the fungal pathogen *Pseudogymnoascus destructans*) are a growing threat to endemic cave fauna (i.e. bats; Reeves 2001; Elliott et al. 2017), particularly in shallow caves, cave mouths, and rock shelters at lower elevations (Vuln. Assessment Workshop, pers. comm., 2017).

Fire suppression
Summary of Potential Impacts on Species Group • The use of phosphorus-based fire retardant can cause eutrophication in subsurface aquatic systems, such as those associated with karst terrain and lava tubes (Tobin et al. 2015; Vuln. Assessment Workshop, pers. comm., 2017).

[5] Non-climate stressors presented are those ranked as having a moderate or higher impact on one or more habitats considered in this group; additional non-climate stressors that that may influence the habitat to a lesser degree include agriculture, dams, roads/highways/trails, timber harvest/clearcuts, mining, and recreation.

• On serpentine and other low-nutrient substrates, the use of fire retardant can increase vulnerability to invasive species by enhancing nutrient availability (Vuln. Assessment Workshop, pers. comm., 2017).
Livestock grazing
Summary of Potential Impacts on Species Group • Historical and modern livestock trampling negatively impacts rock shelters near grazing locations, and climate change could increase the use of shelters by livestock as they seek to escape from heat (Vuln. Assessment Reviewer, pers. comm., 2019). • Livestock are also associated with the introduction of invasive species (Vuln. Assessment Workshop, pers. comm., 2017).

Adaptive Capacity

Both surface and subsurface endemic habitats were evaluated by regional experts as having low-moderate overall adaptive capacity (high confidence in evaluation; see Table 4).

Table 4. Adaptive capacity factors that influence the ability of endemic habitats to adapt to projected future climate changes. Factors that receive a ranking of "High" enhance adaptive capacity for this habitat (+), while factors that receive a ranking of "Low" undermine adaptive capacity (-).

Adaptive Capacity Factors	
Habitat extent, integrity, continuity, and permeability **Surface habitats:** Moderate extent (high confidence), moderate-high integrity (high confidence), low continuity (high confidence), low-moderate landscape permeability (high confidence) **Subsurface habitats:** Moderate extent (high confidence), moderate-high integrity (moderate confidence), low continuity (high confidence), low	• Endemic habitats are naturally isolated by the unique combination of edaphic conditions that define them. Associated plant communities are also comprised of isolated populations of species adapted to those conditions (Whittaker 1960; Kruckeberg 1986, 1991; Damschen et al. 2012). • Across disconnected sites such as rock outcrops, ridgetops, and rare soil types, there is little opportunity for dispersal and gene exchange by plants that lack adaptations for long-distance seed dispersal and animals that are sedentary or have small ranges (Damschen et al. 2012; Cunze et al. 2013; Zika et al. 2018). However, this isolation exerts a strong selective pressure on organisms, promoting adaptation and diversification in response to extreme edaphic conditions (Kruckeberg 1986; Ackerly 2003; Brady et al. 2005; Schenk et al. 2018). These adaptations give edaphic endemic plants an advantage over more generalist species, but they are often unable to compete with soil generalists (Damschen et al. 2012). • Plant dispersal limitations are likely to prevent migration in many naturally isolated habitats, and any distributional shifts that do occur may not occur at a rate comparable to the velocity of regional climate change (Loarie et al. 2008; Damschen et al. 2012; Cunze et al. 2013). • Anthropogenic barriers (e.g., land-use conversion) are likely to further limit the potential migration of many rare plant species in response to climate change (Anacker et al. 2013).

landscape permeability (high confidence)	• The integrity of serpentine plant communities is threatened by the existing presence of exotic species, and increasingly by habitat fragmentation and modification as a result of human land-use conversion and associated activities (Harrison & Viers 2007 and citations therein). For example, habitat fragmentation may reduce serpentine resilience to invasion by decreasing patch size (Harrison & Viers 2007 and citations therein).

Habitat diversity
 	
Surface habitats: High physical/topographical diversity (high confidence), low-moderate species diversity (low confidence), low-moderate functional group diversity (low confidence)
 	
Subsurface habitats: High physical/ topographical diversity (high confidence), moderate species diversity (low confidence), low-moderate functional group diversity (low confidence)
	• The Klamath-Siskiyou Mountains have a complex geologic history that has resulted in highly diverse topography as well as a wide range of rock types and parent materials occurring in the region. Although they remain relatively rare, the region contains an unusually high concentration of ultramafic substrates (i.e., peridotite and serpentine intrusions) and carbonate rocks (e.g., limestone, dolomite; Whittaker 1960).
	  ○ Other factors that contribute to the high heterogeneity of endemic habitats in northern California are strong climatic gradients and variable disturbance history (Vuln. Assessment Workshop, pers. comm., 2017).
	  ○ Rare endemic plants in areas with high topographic variability, such as in northern California, may be less vulnerable to climate change due to the greater probability of local refugia (Loarie et al. 2008; Anacker et al. 2013; Harrison & Noss 2017).
	• The extreme edaphic conditions characteristic of these substrates, in combination with their naturally fragmented distribution across the landscape, has resulted in high levels of genetic divergence and endemism observed in these habitats (Kruckeberg 1986, 1991; Ackerly 2003; Alexander et al. 2007; O'Dell & Rajakaruna 2011; Schenk et al. 2018).
	• The California Floristic Province (which includes California and small portions of Oregon, Nevada, and Baja California) likely has more edaphic specialists than any other floristic province in the world (Harrison 2013).
	  ○ As of 2001, 879 (43%) of the state's 2,058 special-status taxa (i.e., rare, threatened, or endangered species, subspecies, or varieties) are edaphic specialists. Of those, the largest proportion (298) are associated with serpentine substrates (CNPS 2001 and CDFW 2004 cited in Harrison 2013).
	  ○ Safford et al. (2005) estimate that 12.5% of the state's endemic species are broadly or strictly associated with serpentine, even though this substrate only accounts for 2% of the state's area. Northwestern California has the highest serpentine endemic plant diversity in the state (Safford et al. 2005).
	• Similar to the diversity of surface topography, subsurface caves, rock shelters, and lava tubes have created uniquely isolated microclimate islands for subterranean species, including many rare and endemic bats, salamanders, and invertebrates (e.g., arachnids, millipedes, springtails, ice crawlers, and beetles, among others; Elliott et al. 2017)
	  ○ In northern California, Samwell Cave and Shasta Caverns are particularly noted for their high biodiversity (Elliott et al. 2017).
	• The high levels of species endemism in caves is due to a combination of extreme environmental conditions (which includes relatively stable temperature/humidity within cave interiors), natural isolation in scattered

	caves, and the limited dispersal ability of cave-dwellers, among other factors (Barr & Holsinger 1985; Culver et al. 2000; Lefébure et al. 2006). o In general, cave entrance species are considered more vulnerable to climate change than deep cave dwellers due to more variable conditions (Vuln. Assessment Workshop, pers. comm., 2017). • On rock outcrops, cliffs, and talus slopes, overstory plants (e.g., trees, shrubs) are considered foundational species because they control light/shade and moisture/evapotranspiration, creating favorable microclimates for other species (Vuln. Assessment Workshop, pers. comm., 2017). o Lichens and mesic understory plants may be particularly sensitive to climate change (Vuln. Assessment Workshop, pers. comm., 2017).
Resistance and recovery **Surface habitats:** Moderate-high resistance (moderate confidence), low recovery (moderate confidence) **Subsurface habitats:** Moderate-high resistance (moderate confidence), low recovery (high confidence)	• Low dispersal capacity among many endemic species reduces the potential for population recovery/colonization following disturbance (Vuln. Assessment Workshop, pers. comm., 2017). • Serpentine habitats are relatively resilient to changing climatic conditions and exotic invasion because endemic plants are adapted to harsh growing conditions that exclude most habitat generalists (Eskelinen & Harrison 2013). • The nature of caves generally keeps them from changing rapidly (Badino 2010; Covington & Perne 2016); however, once they are disturbed or altered they also recover very slowly (Vuln. Assessment Workshop, pers. comm., 2017). • Rock outcrops, cliffs, and talus slopes are drought-prone environments and can experience extreme temperature fluctuations, so inhabitants are typically adapted to tolerate those conditions. Overall, humans have not had a significant impact on these habitats (Vuln. Assessment Workshop, pers. comm., 2017). • Rocky habitats and talus slopes in alpine ecosystems are expected to experience dramatic warming and may exhibit signs of change before other terrestrial ecosystems because of their high sensitivity to disturbance (Rundel & Millar 2016).
Public and societal value **Surface and subsurface habitats:** Low-moderate value (high confidence)	• Endemic habitats are valued by the public for genetic/evolutionary diversity, aesthetic (beautiful plants), charismatic species (bats), and uniqueness/rarity (Vuln. Assessment Workshop, pers. comm., 2017). • Although state and federal policy support exists to protect rare endemic species (e.g., through state- and federal endangered species regulations; O'Dell 2014), little financial support for management is available (Vuln. Assessment Workshop, pers. comm., 2017). *Surface habitats* • The aesthetic value of rock outcrops, cliffs, and talus slopes is very high, even where flora and fauna are largely absent (Vuln. Assessment Workshop, pers. comm., 2017). • Societal support for management of rock outcrops, cliffs, and talus slopes is increased by rock climbers, wildflower enthusiasts, bird-watchers (looking for cliff-nesting raptors), wilderness societies, the Sierra Club, and the California Native Plant Society (Vuln. Assessment Workshop, pers. comm., 2017).

	• The reintroduction of condors could influence societal support for management (Vuln. Assessment Workshop, pers. comm., 2017). *Subsurface habitats* • Caves have very high value to some northern California tribes (Vuln. Assessment Workshop, pers. comm., 2017). • Northern California has many caves on public lands (primarily National Forests) that are subject to protection via the Federal Cave Resources Protection Act of 1998 (16 USC 4301-4309; Elliott et al. 2017). The Federal Land Policy and Management Act of 1976 (PL 94-79) also prohibits destruction of caves and disturbance of cave fauna such as bats (Elliott et al. 2017). At the state level, the California Cave Protection Act protects all caves and cave features and prohibits disturbing bats and other organisms (Elliott et al. 2017). • The National Speleological Society (national advocacy group) increases interest and conservation engagement (e.g., creation of the Klamath Mountain Conservation Task Force to organize the exploration and conservation of caves in the Marble Mountain karst area; Elliott et al. 2017), and local cavers can be active in northern California (Vuln. Assessment Workshop, pers. comm., 2017). • Gross vandalism, bat-killing diseases, and extinctions could influence societal support for cave management (Vuln. Assessment Workshop, pers. comm., 2017). • Preservation of cultural deposits in caves may improve as humidity and water levels decrease (Vuln. Assessment Workshop, pers. comm., 2017).

Management capacity and ability to alleviate impacts of climate change[6]
 	
Surface and subsurface habitats: Low-moderate capacity/ability (moderate confidence)
	• Although the science and technology exist to support management of endemic habitats, capacity is very low (e.g., institutional will, political/social valuation, labor, funding). Limited interest further contributes to inaction (Vuln. Assessment Workshop, pers. comm., 2017).
	  ○ In order to focus very limited resources, management generally focuses on the areas of most interest to the most people (Vuln. Assessment Workshop, pers. comm., 2017).
	• Use conflicts and competing interests include: people/political groups who have strong opinions but are unwilling to compromise, limited attention spans (unable to move quickly enough). However, there is little development pressure outside of recreation (Vuln. Assessment Workshop, pers. comm., 2017).
	  ○ Recreational activities and livestock use of rock shelters can conflict (Vuln. Assessment Workshop, pers. comm., 2017).
	  ○ Rock climbers can conflict with botanists and birders around the use of rock outcrops, cliffs, and talus slopes (Vuln. Assessment Workshop, pers. comm., 2017).
	• Management efforts focused on maintaining endemic habitats, including rare species, over the coming century should include protection of refugia where

[6] Further information on climate adaptation strategies and actions for northern California can be found on the project page (https://bit.ly/31AUGs5).

	climate conditions are believed to be relatively stable and the velocity of future change may be lower (Harrison & Noss 2017). Additionally, the identification and protection of microrefugia (created by vegetation or small-scale topographic features; Rull 2009; Dobrowski 2011) is critical to the persistence of endemic species (Harrison & Noss 2017). • Management actions focused on the restoration of degraded endemic habitats may include the use of livestock grazing, invasive species control, prescribed fire, native plantings, erosion control, and other techniques focused on revegetation with native plants, manipulating soil properties, and restoring natural hydrology (Safford & Harrison 2008; O'Dell 2014). • Exposure of cliffs if Klamath dams are removed would be an opportunity to study species colonization rates (Vuln. Assessment Workshop, pers. comm., 2017). • The expansion of monitoring efforts in endemic habitats such as caves and high-elevation cliffs and talus slopes could facilitate more effective ecosystem management by highlighting trends in climate conditions and species abundance/diversity (Sarr et al. 2007). For example, the Klamath Network Vital Signs Monitoring Plan (coordinated by the National Park Service) began monitoring cave vital signs in 2017 at Lava Beds National Monument in northeastern California and Oregon Caves Natural Monument and Preserve (Krejca et al. 2017). This program monitors variables that indicate the status of and potential trends in cave climate, water level in subterranean pools, focal species and communities, and human visitation (Krejca et al. 2017). • Little can be done for management of rock outcrops, cliffs, and talus slopes due to the scale of habitat and lack of access (Vuln. Assessment Workshop, pers. comm., 2017). ○ Managers may be able to limit the effects of increased wildfire (Vuln. Assessment Workshop, pers. comm., 2017).

Ecosystem services	• Workshop participants noted that endemic habitats provide a variety of ecosystem services, including:
	    ○ Provisioning of food, fiber, genetic resources and plant breeding, natural medicines, ornamental resources, and fresh water;
	    ○ Regulation of water purification (lava) and natural hazards;
	    ○ Support of water cycling; and
	    ○ Cultural/tribal uses for spiritual/religious purposes, knowledge systems, educational values, aesthetic values, social relations, sense of place, cultural heritage, inspiration, and recreation (Vuln. Assessment Workshop, pers. comm., 2017).
	• In addition to their important contribution to regional biodiversity, edaphic endemic plant species play an important role in reducing environmental hazards through restoration or phytoremediation of extreme substrates (O'Dell 2014). For example, revegetation of contaminated mine sites can reduce air and water pollution (USEPA 2011 cited in O'Dell 2014).
	• Endemic habitats that are buffered from extreme fluctuations in temperature (e.g., caves, talus slopes) may provide climate refugia for both edaphic specialists and generalist species over the coming century (Rundel & Millar

	2016; Elliott et al. 2017). For instance, rock shelters and cave mouths can provide cool microclimates for terrestrial species (Sarr et al. 2007). Abandoned mines, which are widespread, may also provide seasonal thermal refugia for cave-dwelling species (Elliott et al. 2017). • Endemic habitats and associated edaphic specialists provide ideal model systems for research (Rajakaruna 2018). • Bat caves provide ecosystem services to both subterranean water bodies and surrounding terrestrial vegetation, with the latter occurring via nightly bat visits that can provide seed dispersal, pollination, and pest control (Medellin et al. 2017). • Tribes also value high-elevation rocky habitats as areas of spiritual retreat (York et al. 1993), vantage points for hunting/seeking game, and areas from which to view the impacts of fire and predicting weather and seasonal changes (Turner et al. 2011).

Recommended Citation

Sims, SA, Hilberg LE, Reynier WA, Kershner JM. 2020. Endemic Habitats: 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.

Ackerly DD. 2003. Community assembly, niche conservatism, and adaptive evolution in changing environments. International Journal of Plant Sciences **164**:S165–S184.

AghaKouchak A, Ragno E, Love C, Moftakhari H. 2018. Projected changes in California's precipitation intensity-frequency curves. California's Fourth Climate Change Assessment. Publication Number: CCCA4-CEC-2018-005. California Energy Commission, Sacramento, CA.

Aho K, Weaver T, Eversman S. 2014. Water and substrate control of cliff communities: patterns among species and phyla. Journal of Vegetation Science **25**:1381–1393.

Alexander EB, Coleman RG, Harrison SP, Keeler-Wolfe T. 2007. Serpentine geoecology of western North America: geology, soils, and vegetation. Oxford University Press, New York, NY.

Anacker BL, Gogol-Prokurat M, Leidholm K, Schoenig S. 2013. Climate change vulnerability assessment of rare plants in California. Madroño **60**:193–210.

Anacker BL, Rajakaruna N, Ackerly DD, Harrison SP, Keeley JE, Vasey MC. 2011. Ecological strategies in California chaparral: interacting effects of soils, climate, and fire on specific leaf area. Plant Ecology and Diversity **4**:179–188.

Badino G. 2004. Cave temperatures and global climatic change. International Journal of Speleology **33**:10.

Badino G. 2010. Underground meteorology: "What's the weather underground?" Acta Carsologica **39**:427–448.

Barr TC Jr, Holsinger JR. 1985. Speciation in cave faunas. Annual Review of Ecology and Systematics **16**:313–337.

Billings WD. 1950. Vegetation and plant growth as affected by chemically altered rocks in the western Great Basin. Ecology **31**:62–74.

Bishop J. 2010. Using alpine flora to measure ecoregional effects of climate change. Fremontia **38**:2–9.

Brady KU, Kruckeberg AR, Bradshaw HD Jr. 2005. Evolutionary ecology of plant adaptation to serpentine soils. Annual Review of Ecology, Evolution, and Systematics **36**:243–266.

Brooks ML, Brown CS, Chambers JC, D'Antonio CM, Keeley JE, Belnap J. 2016. Exotic annual *Bromus invasions*: comparisons among species and ecoregions in the western United States. Pages 11–60 in M. J. Germino, J. C. Chambers, and C. S. Brown, editors. Exotic brome-grasses in arid and semiarid ecosystems of the western US. Springer International Publishing, Switzerland.

CDFW. 2018. Status review of Lassics lupine (*Lupinus constancei*). Report to the California Fish and Game Commission. California Department of Fish and Wildlife, Sacramento, CA.

Cook BI, Ault TR, Smerdon JE. 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Science Advances **1**:e1400082.

Cooper DJ, Wolf EC. 2007. A restoration and monitoring plan for *Puccinellia howellii*, Whiskeytown National Recreation Area, California. Colorado State University, Fort Collins, CO. Available from https://sites.warnercnr.colostate.edu/davidcooper/wp-content/uploads/sites/15/2017/02/Restoration-Report-CooperWolf-FINAL.pdf (accessed July 2, 2019).

Copeland SM, Harrison SP, Latimer AM, Damschen EI, Eskelinen AM, Fernandez-Going B, Spasojevic MJ, Anacker BL, Thorne JH. 2016. Ecological effects of extreme drought on Californian herbaceous plant communities. Ecological Monographs **86**:295–311.

Covington MD, Perne M. 2016. Consider a cylindrical cave: a physicist's view of cave and karst science. Acta Carsologica **44**:363–380.

Culver DC, Master LL, Christman MC, Hobbs HH III. 2000. Obligate cave fauna of the 48 contiguous United States. Conservation Biology **14**:386–401.

Cunze S, Heydel F, Tackenberg O. 2013. Are plant species able to keep pace with the rapidly changing climate? PLOS ONE **8**:e67909.

Damschen EI, Harrison S, Ackerly DD, Fernandez-Going BM, Anacker BL. 2012. Endemic plant communities on special soils: early victims or hardy survivors of climate change? Journal of Ecology **100**:1122–1130.

Damschen EI, Harrison S, Grace JB. 2010. Climate change effects on an endemic-rich edaphic flora: resurveying Robert H. Whittaker's Siskiyou sites (Oregon, USA). Ecology **91**:3609–3619.

Dettinger M. 2011. Climate change, atmospheric rivers, and floods in California – a multimodel analysis of storm frequency and magnitude changes. Journal of the American Water Resources Association **47**:514–523.

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.

Dukes JS, Mooney HA. 2004. Disruption of ecosystem processes in western North America by invasive species. Revista Chilena de Historia Natural **77**:411–437.

Elliott WR, Reddell JR, Rudolph DC, Graening GO, Briggs TS, Ubick D, Aalbu RL, Krejca J, Taylor SJ. 2017. The cave fauna of California. Proceedings of the California Academy of Sciences, Series 4, Volume 64, Supplement 1. California Academy of Sciences, San Francisco, CA.

Eskelinen A, Harrison S. 2013. Exotic plant invasions under enhanced rainfall are constrained by soil nutrients and competition. Ecology **95**:682–692.

Fernandez-Going BM, Anacker BL, Harrison SP. 2012. Temporal variability in California grasslands: soil type and species functional traits mediate response to precipitation. Ecology **93**:2104–2114.

Fernandez-Going BM, Harrison S. 2013. Effects of experimental water addition depend on grassland community characteristics. Plant Ecology **214**:777–786.

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.

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.

Gershunov A, Guirguis K. 2012. California heat waves in the present and future. Geophysical Research Letters **39**:L18710.

Grantham TEW, Carlisle DM, McCabe GJ, Howard JK. 2018. Sensitivity of streamflow to climate change in California. Climatic Change **149**:427–441.

Griffin D, Anchukaitis KJ. 2014. How unusual is the 2012–2014 California drought? Geophysical Research Letters **41**:9017–9023.

Groves C, Meiman J. 2005. Flooding. Pages 251–254 in W. B. White and D. Culver, editors. Encyclopedia of caves. Elsevier Academic Press, Burlington, MA.

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.

Harper GD. 1984. The Josephine ophiolite, northwestern California. GSA Bulletin **95**:1009–1026.

Harrison S. 2013. Plant and animal endemism in California. University of California Press, Berkeley, CA.

Harrison S, Damschen E, Fernandez-Going B, Eskelinen A, Copeland S. 2015a. Plant communities on infertile soils are less sensitive to climate change. Annals of Botany **116**:1017–1022.

Harrison S, Inouye BD, Safford HD. 2003. Ecological heterogeneity in the effects of grazing and fire on grassland diversity. Conservation Biology **17**:837–845.

Harrison S, Noss R. 2017. Endemism hotspots are linked to stable climatic refugia. Annals of Botany **119**:207–214.

Harrison SP, Gornish ES, Copeland S. 2015b. Climate-driven diversity loss in a grassland community. Proceedings of the National Academy of Sciences of the United States of America **112**:8672–8677.

Harrison SP, Viers JH. 2007. Serpentine grasslands. Pages 145–155 in M. R. Stromberg, J. D. Corbin, and C. M. D'Antonio, editors. California grasslands: ecology and management. University of California Press, Berkeley, CA.

Huenneke LF, Hamburg SP, Koide R, Mooney HA, Vitousek PM. 1990. Effects of soil resources on plant invasion and community structure in Californian serpentine grassland. Ecology **71**:478–491.

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.

Kilburn CRJ. 2000. Lava flows and flow fields. Pages 291–305 in H. Sigurdsson, editor. Encyclopedia of volcanoes. Academic Press, San Diego, CA.

Kinkel AR Jr, Hall WE, Albers JP. 1956. Geology and base-metal deposits of West Shasta copper-zinc district, Shasta County, California. Geological Survey Professional Paper 285. U.S. Geological Survey, Washington, D.C.

Körner C. 2003. Alpine plant life: functional plant ecology of high mountain ecosystems. Springer Verlag, Berlin.

Körner C. 2007. Climatic treelines: conventions, global patterns, causes. Erdkunde **61**:316–324.

Krejca JK, Myers III GR, Chung-MacCoubrey A, Dinger EC, Mohren S, Riggs D, Sarr D, Smith K, Snyder A, Thomas S. 2017. Integrated monitoring protocol for cave entrance communities and cave environments in the Klamath Network. Version 1.0. Natural Resource Report NPS/KLMN/NRR—2017/1400. National Park Service, Fort Collins, CO.

Kruckeberg AR. 1984. California serpentines: flora, vegetation, geology, soils, and management problems. University of California Press, Berkeley, CA.

Kruckeberg AR. 1986. An essay: the stimulus of unusual geologies for plant speciation. Systematic Botany **11**:455–463.

Kruckeberg AR. 1991. An essay: geoedaphics and island biogeography for vascular plants. Aliso: A Journal of Systematic and Evolutionary Botany **13**:225–238.

Kruckeberg AR. 2006. Introduction to California soils and plants: serpentine, vernal pools, and other geobotanical wonders. University of California Press, Berkeley, CA.

Kulonen A, Imboden RA, Rixen C, Maier SB, Wipf S. 2017. Enough space in a warmer world? Microhabitat diversity and small-scale distribution of alpine plants on mountain summits. Diversity and Distributions **24**:252–261.

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.

Lee NM, Meisinger DB, Aubrecht R, Kovacik L, Saiz-Jimenez C, Baskar S, Baskar R, Liebl W, Porter ML, Engel AS. 2012. Caves and karst environments. Pages 320–344 in E. M. Bell, editor. Life at extremes: environments, organisms, and strategies for survival. CABI Publishing, Cambridge, MA.

Lefébure T, Douady CJ, Gouy M, Trontelj P, Briolay J, Gibert J. 2006. Phylogeography of a subterranean amphipod reveals cryptic diversity and dynamic evolution in extreme environments. Molecular Ecology **15**:1797–1806.

Lembrechts JJ, Lenoir J, Nuñez MA, Pauchard A, Geron C, Bussé G, Milbau A, Nijs I. 2018. Microclimate variability in alpine ecosystems as stepping stones for non-native plant establishment above their current elevational limit. Ecography **41**:900–909.

Loarie SR, Carter BE, Hayhoe K, McMahon S, Moe R, Knight CA, Ackerly DD. 2008. Climate change and the future of California's endemic flora. PLoS ONE **3**:e2502.

Luckman BH. 2013. Talus slopes. Pages 566–573 in S. A. Elias, editor. The Encyclopedia of Quaternary Science. Elsevier, Amsterdam.

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.

Medellin RA, Wiederholt R, Lopez-Hoffman L. 2017. Conservation relevance of bat caves for biodiversity and ecosystem services. Biological Conservation **211**:45–50.

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.

Nelson JK, Lindstrand L. 2015. A new species Of *Vaccinium* (Ericaceae) from the southeastern Klamath Mountains and the Sierra Nevada, California, with two subspecies. Madroño **62**:167–180.

O'Dell RE. 2014. Conservation and restoration of chemically extreme edaphic endemic flora in the western US. Pages 313–364 in N. Rajakaruna, R. S. Boyd, and T. B. Harris, editors. Plant ecology and evolution in harsh environments. Nova Science Publishers, Hauppauge, NY.

O'Dell RE, Rajakaruna N. 2011. Intraspecific variation, adaptation, and evolution. Pages 97–137 in S. Harrison and N. Rajakaruna, editors. Serpentine: the evolution and ecology in a model system. University of California Press, Berkeley, CA.

Parisi MD. 1988. Barren. In K. E. Mayer and W. F. Laudenslayer Jr., editors. A guide to wildlife habitats of California. California Department of Fish and Game, Sacramento, CA. Available from https://www.wildlife.ca.gov/Data/CWHR/Wildlife-Habitats.

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.

Pauchard A et al. 2009. Ain't no mountain high enough: plant invasions reaching new elevations. Frontiers in Ecology and the Environment **7**:479–486.

Pérez FL. 1998. Conservation of soil moisture by different stone covers on alpine talus slopes (Lassen, California). Catena **33**:155–177.

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.

Pitcairn M, Schoenig S, Yacoub R, Gendron J. 2006. Yellow starthistle continues its spread in California. California Agriculture **60**:83–90.

Rajakaruna N. 2004. The edaphic factor in the origin of plant species. International Geology Review **46**:471–478.

Rajakaruna N. 2018. Lessons on evolution from the study of edaphic specialization. The Botanical Review **84**:39–78.

Rajakaruna N, Boyd RS, Harris TB. 2014. Synthesis and future directions: what have harsh environments taught us about ecology, evolution, conservation, and restoration? Pages 393–409 in N. Rajakaruna, R. S. Boyd, and T. B. Harris, editors. Plant ecology and evolution in harsh environments. Nova Science Publishers, Hauppauge, NY.

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.

Reeves WK. 2001. Exotic species in North American caves. Pages 164–166 in T. Rea, editor. Living with caves and karst: Proceedings of the 14th National Cave & Karst Management Symposium, Chattanooga, Tennessee, USA, October 1999. Southeastern Cave Conservancy, Inc., Chattanooga, TN.

Rejmánek M. 2018. Vascular plant extinctions in California: a critical assessment. Diversity and Distributions **24**:129–136.

Rossington N, Yost J, Ritter M. 2018. Water availability influences species distributions on serpentine soils. Madroño **65**:68–79.

Rull V. 2009. Microrefugia. Journal of Biogeography **36**:481–484.

Rundel PW, Keeley JE. 2016. Dispersal limitation does not control high elevational distribution of alien plant species in the southern Sierra Nevada, California. Natural Areas Journal **36**:277–287.

Rundel PW, Millar CI. 2016. Alpine ecosystems. Pages 613–634 in H. Moody and E. Zavaleta, editors. Ecosystems of California. University of California Press, Oakland, CA.

Safford HD, Harrison S. 2004. Fire effects on plant diversity in serpentine vs. sandstone chaparral. Ecology **85**:539–548.

Safford HD, Harrison SP. 2008. The effects of fire on serpentine vegetation and implications for management. Pages 321–328 in M. G. Narog, editor. Proceedings of the 2002 fire conference: managing fire and fuels in the remaining wildlands and open spaces of the Southwestern United

States. Gen. Tech. Rep. PSW-GTR-189. 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.

Safford HD, Viers JH, Harrison SP. 2005. Serpentine endemism in the California flora: a database of serpentine affinity. Madroño **52**:222–257.

Salisbury FB. 1954. Some chemical and biological investigations of materials derived from hydrothermally altered rock in Utah. Soil Science **78**:277.

Salisbury FB. 1964. Soil formation and vegetation on hydrothermally altered rock material in Utah. Ecology **45**:1–9.

Sánchez-Fernández D, Rizzo V, Cieslak A, Faille A, Fresneda J, Ribera I. 2016. Thermal niche estimators and the capability of poor dispersal species to cope with climate change. Scientific Reports **6**:23381.

Sarr DA, Odion DC, Mohren SR, Perry EE, Hoffman RL, Bridy LK, Merton AA. 2007. Klamath Network vital signs monitoring plan. Natural Resource Report, NPS/KLMN/NRR-2007/016. USDOI National Park Service, Klamath Network Inventory and Monitoring Program, Ashland, OR.

Saslis-Lagoudakis CH, Moray C, Bromham L. 2014. Evolution of salt tolerance in angiosperms: a phylogenetic approach. Pages 77–95 in N. Rajakaruna, R. S. Boyd, and T. B. Harris, editors. Plant ecology and evolution in harsh environments. Nova Science Publishers, Hauppauge, NY.

Schenk JJ, Kontur S, Wilson H, Noble M, Derryberry E. 2018. Allopatric speciation drives diversification of ecological specialists on sandhills. International Journal of Plant Sciences **179**:325–339.

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.

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.

Swain DL, Langenbrunner B, Neelin JD, Hall A. 2018. Increasing precipitation volatility in twenty-first-century California. Nature Climate Change **8**:427.

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, 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.

Tobin BW, Schwartz BF, Kelly M, Despain JD. 2015. Fire retardant and post-fire nutrient mobility in a mountain surface water—karst groundwater system: the Hidden Fire, Sequoia National Park, California, USA. Environmental Earth Sciences **73**:951–960.

Turner NJ, Deur D, Mellott CR. 2011. "Up on the mountain": ethnobotanical importance of montane sites in Pacific Coastal North America. Journal of Ethnobiology **31**:4–43.

Vallano DM, Selmants PC, Zavaleta ES. 2012. Simulated nitrogen deposition enhances the performance of an exotic grass relative to native serpentine grassland competitors. Plant Ecology **213**:1015–1026.

Vitousek PM, D'Antonio CM, Loope LL, Rejmánek M, Westbrooks R. 1997. Introduced species: a significant component of human-caused global change. New Zealand Journal of Ecology **21**:1–16.

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.

Weiss SB. 1999. Cars, cows, and checkerspot butterflies: nitrogen deposition and management of nutrient-poor grasslands for a threatened species. Conservation Biology **13**:1476–1486.

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.

Whittaker RH. 1960. Vegetation of the Siskiyou Mountains, Oregon and California. Ecological Monographs **30**:279–338.

Winter TC, Harvey JW, Franke OL, Alley WM. 1998. Ground water and surface water: a single resource. Circular 1139. U.S. Geological Survey, Reston, VA.

Wolf A, Zimmerman NB, Anderegg WRL, Busby PE, Christensen J. 2016. Altitudinal shifts of the native and introduced flora of California in the context of 20th-century warming. Global Ecology and Biogeography **25**:418–429.

Wright JE, Wyld SJ. 1994. The Rattlesnake Creek terrane, Klamath Mountains, California: an early Mesozoic volcanic arc and its basement of tectonically disrupted oceanic crust. GSA Bulletin **106**:1033–1056.

Xiao S, Callaway RM, Graebner R, Hierro JL, Montesinos D. 2016. Modeling the relative importance of ecological factors in exotic invasion: the origin of competitors matters, but disturbance in the non-native range tips the balance. Ecological Modelling **335**:39–47.

York A, Daly R, Arnett C. 1993. They write their dreams on the rocks forever: rock writings in the Stein River Valley of British Columbia. Talonbooks, Vancouver, B.C.

Yost JM, Barry T, Kay KM, Rajakaruna N. 2012. Edaphic adaptation maintains the coexistence of two cryptic species on serpentine soils. American Journal of Botany **99**:890–897.

Zika PF, Wilson BL, Brainerd RE, Otting N, Darington S, Knaus BJ, Nelson JK. 2018. A review of *Sedum* section *Gormania* (Crassulaceae) in western North America. Phytotaxa **368**:1–61.

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),[7] 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.[8]

[7] Sensitivity and adaptive capacity elements were informed by Lawler 2010, Glick et al. 2011, and Manomet Center for Conservation Sciences 2012.

[8] 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:

Vulnerability = [(Climate Exposure*0.5) x Sensitivity] - 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.