Alpine Grasslands and Shrublands
Northern California Climate Change Vulnerability Assessment Synthesis

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for alpine grasslands and shrublands 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 Alison Colwell (University of California, Berkeley), Anonymous (retired U.S. Forest Service), and Julie Nelson (U.S. Forest Service). Vulnerability scores were provided by Redding workshop participants.

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Habitat Description

In northern California, alpine grasslands and shrublands generally occur above treeline or in scattered openings amongst subalpine vegetation in high-montane areas, including the Klamath Mountains and the southern Cascades (USDA Forest Service 2009a, 2009b; Rundel & Millar 2016). Alpine habitats are characterized by extreme conditions, including cold winter temperatures, short growing seasons (July-August), high wind, low nutrient availability, low water availability, low partial pressures of carbon dioxide (CO_2), and high UV irradiance (Rundel

& Millar 2016). Alpine grasslands and shrublands experience a montane Mediterranean climate, featuring dry summers and wet winters where precipitation largely falls as snow (Rundel & Millar 2016).

Vegetation composition in alpine grasslands and shrublands is influenced by harsh growing conditions, as well as by topography and substrate (Skinner et al. 2006; Sawyer & Keeler-Wolf 2007; Rundel & Millar 2016). Across the study region, vegetation in alpine grasslands and shrublands is typically perennial and includes two functional groups: herbaceous species (e.g., cushion plants, tufted or rhizomatous graminoids) and less commonly, dwarf or low prostrate shrubs (Thorne et al. 2016). Stunted "krummholz" trees may also occur along the treeline (Skinner et al. 2006; Sawyer & Keeler-Wolf 2007). For the purposes of this assessment, we are including the alpine mixed scrub alliance and the alpine grasses and forbs alliance as described in the USDA Forest Service Region 5 CALVEG classification system (USDA Forest Service 2009a, 2009b). Across the northern California region, common herbaceous species in these alliances include Indian paintbrush (*Castilleja* spp.), mountain sorrel (*Oxyria digyna*), *Draba* spp., sibbaldia (*Sibbaldia procumbens*), and rock cress (*Arabis* spp.; USDA Forest Service 2009a, 2009b). Common shrubs include mountain heather (*Phyllodoce empetriformis*) and white heather (*Cassiope mertensiana*; USDA Forest Service 2009a, 2009b).

Alpine areas have important cultural, spiritual, wilderness, and recreational values for a variety of societal groups (Turner et al. 2011; USDA Forest Service 2012; Norgaard et al. 2016). For example, regional Native American tribes utilize alpine meadows and adjacent subalpine parklands to procure critical food, medicinal, fiber, and material resources (Turner et al. 2011; Norgaard et al. 2016).

Executive Summary

The relative vulnerability of alpine grasslands and shrublands 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.

Alpine Grasslands and Shrublands	Rank	Confidence
Sensitivity	Moderate-High	Moderate
Future Exposure	Moderate	Moderate
Adaptive Capacity	Low-Moderate	Moderate
Vulnerability	**Moderate**	**Moderate**

Sensitivity & Exposure Summary	
	Climate and climate-driven factors: • Air temperature, heat waves, snowpack amount, timing of snowmelt and runoff, precipitation amount and timing, drought, soil moisture, climatic water deficit *Disturbance regimes*: • Wildfire, volcanic events *Non-climate stressors*: • Invasive and other problematic species, recreation, trails

Alpine grasslands and shrublands are primarily sensitive to factors that alter moisture availability and the initiation and length of the growing season, including increasing air temperature, reduced snowpack depth, earlier snowmelt timing, changes in precipitation amount, timing and duration, increased drought and heat wave activity, reduced soil moisture, and increased climatic water deficit. These factors alter plant distribution, germination capacity, plant growth, herbivory, and survival, and can lead to shifts in species composition. Warmer temperatures may also facilitate replacement of alpine grasslands and shrublands with lower-elevation species. Although rare, wildfire and volcanic activity can reset alpine grassland and shrubland succession and change the landscape distribution of this habitat type. Relative to other habitats, alpine grasslands and shrublands have low sensitivity and exposure to non-climate stressors due to their remote location. However, exotic species may become more prevalent with climate change, increasing competition for already limited resources. Recreational activities and trails can act as vectors and dispersal corridors for exotic species introductions, and also facilitate habitat degradation via trampling and erosion.

Adaptive Capacity Summary	*Factors that enhance adaptive capacity*: + Moderate habitat integrity + Moderate-high topographical and physical diversity + Valued for recreation, spiritual, and cultural activities, and for aesthetics + Provide many ecosystem services *Factors that undermine adaptive capacity*: – Limited habitat extent and continuity in study region – Limited or no migration potential – Vegetation not resilient to increasing amplitude of disturbance and climate change – Low functional group diversity – Limited opportunity to manage climate stressors

Alpine grasslands and shrublands have limited distribution in northern California, occurring only in highest elevations of the southern Cascades and the Klamath Mountains. Alpine grasslands and shrublands have limited or no migration opportunity in the face of climate change because they already exist at the highest regional elevations. Remote, high-elevation habitat locations have helped to protect habitat integrity and promote flora adapted to harsh growing conditions, but generally, alpine grasslands and shrublands recover slowly from disturbance and are not resilient to increasing disturbance, competition, or the accelerated rate of climate change. Although these habitats only have two plant functional groups, high topographic and physical diversity drives high species diversity, with significant variation in species composition from site to site. Alpine areas are valued for a variety of cultural, spiritual, and recreational activities, and provide a variety of ecosystem services. Management in alpine grasslands and shrublands will likely focus on opportunities to control non-climate anthropogenic stressors, and may involve integrating cultural management objectives and uses with federal public land management objectives in these areas.

Sensitivity and Exposure

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

Potential Changes in Habitat Distribution by 2100
• 33–97% of current alpine grassland and shrubland habitat across California could become climatically exposed by the end of the century • Northern California may experience close to complete loss of climatic suitability for alpine grassland and shrubland habitats
Source(s): Thorne et al. 2016

Alpine grassland and shrubland distribution is likely to decline in the future as a result of climate change. Modeling by Thorne et al. (2016, 2017) projects that 33–97% of currently occupied habitat across the state will likely become climatically exposed by the end of the century, with only 0–17% of currently occupied habitat projected to remain climatically suitable by the end of the century.[1] Hotter and drier future conditions are projected to cause more alpine habitat to become climatically exposed than warmer and wetter future conditions (Thorne et al. 2016, 2017). Northern California, in particular, is projected to lose most or all potentially climatically suitable areas for alpine grassland and shrubland species (Thorne et al. 2016). Refugia for this habitat type, and for higher elevation species in general, will likely occur outside of the study region in the southern and central Sierra Nevada (Loarie et al. 2008; Thorne et al. 2016) or northward in the Cascade Range (Vuln. Assessment Reviewers, pers. comm., 2018). Existing alpine areas in northern California will likely act as refugia for other vegetation types (e.g., subalpine conifers), eventually excluding alpine grassland and shrubland species (Loarie et al. 2008; Thorne et al. 2016).

Sensitivity and future exposure to climate and climate-driven factors

Regional experts evaluated alpine grasslands and shrublands as having high 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 (low confidence). Key climatic factors that affect alpine grasslands and shrublands include air temperature, heat waves, snowpack amount, precipitation amount and timing, timing of snowmelt and runoff, drought, soil moisture, and climatic water deficit.[2]

[1] Projections in this study are based on two different future climate models, MIROC ESM (warmer and drier) and CNRM CM5 (warmer and wetter), and two future greenhouse gas emissions scenarios, RCP 8.5 (business as usual emissions) and RCP 4.5 (Paris Accord target emissions). These scenarios encompass minimum temperature increases of 1.9–4.5°C (3.42–8.1°F) and a -24.8 to +22.9% change in precipitation by 2100 relative to 1980–2010 (Thorne et al. 2016, 2017).

[2] All climate and climate-driven factors presented were ranked as having a moderate or higher impact on this habitat type.

Air temperature

Increasing air temperatures are likely to have a variety of impacts in alpine grasslands and shrublands, including driving shifts from snow to rain, initiating earlier snowmelt, increasing evaporative stress during the growing season, and raising soil temperatures (Rundel & Millar 2016). Cumulatively, these changes are likely to alter the initiation and length of the growing season and affect alpine vegetation composition, phenology, and productivity (Rundel & Millar 2016).

Air temperature interacts with moisture, nutrients, and other factors to affect alpine plant growth and reproductive success. With available moisture and nutrients, warmer temperatures are likely to increase alpine plant growth (but see climatic water deficit discussion below; Walker et al. 1995). Rising air temperatures will also likely shift the initiation and length of the growing season in alpine grasslands and shrublands (Rundel & Millar 2016). Warmer temperatures leading to earlier snowmelt and elevated soil temperature will likely cause the growing season to start earlier in the year (Walker et al. 1995; Inouye 2008; Rundel & Millar 2016). However, in some areas, warmer air temperatures may also cause an earlier end to the growing season by reducing initial soil moisture inputs from snowpack and increasing summer drought stress via higher evaporative stress (see climatic water deficit discussion below; Price & Waser 2000; Rundel & Millar 2016; Giménez-Benavides et al. 2018). Exact outcomes will vary, with some alpine areas experiencing a longer growing season via an earlier start, and other areas experiencing a shift of the growing season to earlier in the year (Jolly et al. 2005; Rundel & Millar 2016). Changes in growing season length are likely to alter alpine plant reproductive success, but existing experimental warming studies show inconclusive outcomes for flower production and seed output (Giménez-Benavides et al. 2018). Impacts will likely vary depending on plant phenological strategy (e.g., early- vs. late-flowering), but too few comparative studies exist to draw firm conclusions (Giménez-Benavides et al. 2018).

Alterations in growing season initiation and length as a result of warmer temperatures will likely affect alpine grassland and shrubland species composition. For example, warmer temperatures may increase survival and cover of annual herbaceous vegetation (Rundel & Millar 2016). These species have historically been limited in alpine environments due to the challenges of achieving a complete life cycle during short alpine growing seasons (Rundel & Millar 2016). Additionally, warmer temperatures may increase the relative abundance and cover of species that thrive in warmer conditions, while shrinking the abundance and cover of obligate cold species, unless those obligate cold species can migrate to local temperature refugia (e.g., cold air drainages, north-facing slopes; Kulonen et al. 2017).

Community composition changes will also be influenced by which species can successfully alter phenologies to track changing conditions (Rundel & Millar 2016). For example, some alpine species may be able to adapt to earlier snowmelt and an earlier start to the growing season by exhibiting earlier growth and flowering phenologies (Walker et al. 1995; Rundel & Millar 2016). However, species that cannot take advantage of earlier growth opportunities may exhibit reproductive limitations and population declines due to reductions in late-season moisture availability (Giménez-Benavides et al. 2007), especially on southern exposures, with subsequent impacts on other species (e.g., pollinators; Inouye 2008). While alpine plant species have historically exhibited adaptable phenologies as a result of high interannual snowpack and moisture variability resulting from El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) cycles, it is unclear if they will be able to alter their phenology quickly enough to keep pace with projected changes and potentially novel local environmental conditions (Inouye 2008). Additionally, shifting phenologies can expose alpine plants to additional risks, potentially counteracting the positive benefits of a longer growing season (Giménez-Benavides et al. 2018). For example, early-flowering species may experience pollination limitations if pollinators do not track climatic changes at the same rate (i.e., phenological mismatch; Giménez-Benavides et al. 2018).

Increasing air temperatures may also drive loss of alpine grasslands and shrublands to encroachment of lower-elevation vegetation. Various modeling studies project a significant decline in alpine vegetation cover by the end of the century as warmer conditions allow encroachment of lower-elevation vegetation (Hayhoe et al. 2004; California Climate Change Center 2006; Thorne et al. 2016). Daily mean growing season air temperatures above 6.6°C (4.4°F) may allow increased establishment of subalpine tree species (Bishop 2010), effectively shrinking the amount of area in which alpine vegetation holds a competitive advantage and increasing competition for limited resources (Bishop 2010). Historical patterns of forest encroachment support these projections. For example, Taylor (1995) found that mountain hemlock (*Tsuga mertensiana*) seedling establishment in areas above existing subalpine zones on Mt. Lassen were most common in years with higher air temperatures and lower snowpack.

However, the highly diverse microclimates as a result of varied topography and substrates in alpine areas of northern California may buffer alpine vegetation shifts and the extirpation of alpine specialists (Sawyer & Keeler-Wolf 2007; Rundel & Millar 2016). For example, subalpine trees already extend to the highest elevations in the Klamath Mountains, indicating that current distribution and differentiation between alpine and subalpine areas is influenced by substrate (e.g., shallow and/or ultramafic soils) rather than temperature (Skinner et al. 2006; Sawyer & Keeler-Wolf 2007). Similarly, studies in European alpine regions have found that high microtopographical diversity buffers alpine plant extinctions under warming conditions. Microtopographical diversity can create temperature refugia that requires only small horizontal species movement, rather than larger vertical movement (Kulonen et al. 2017). Additionally, substrate diversity can buffer competition. For example, alpine species adapted to growing in scree or on rock surfaces or crevices may be particularly resilient to enhanced competition, as lower-elevation invaders cannot colonize these sites due to low organic soil availability and/or highly mobile substrate (Kulonen et al. 2017). Comparatively, alpine species restricted to soil areas with high organic matter may be most vulnerable to extirpation in a warmer climate, as these more fertile soils will be preferred sites for invasion by lower-elevation species (Kulonen et al. 2017). Organic soil abundance declines with increasing elevation, limiting vertical migration opportunities (Kulonen et al. 2017).

Regional Air Temperature Trends[3]	

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
	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 Klamath Mountain and Southern Cascade ecoregions (Flint et al. 2013; Flint & Flint 2014)
	  ○ 2.0–5.8°C (3.6–10.4°F) increase in average winter minimum temperatures
	  ○ 2.8–6.7°C (5.0–12.1°F) increase in average summer maximum temperatures

Summary of Potential Impacts on Habitat *(see text for citations)*	
• Shifts in growing season length, including earlier growing season initiation and potential earlier end of growing season due to moisture stress • Enhanced plant growth in areas with available moisture • Altered reproductive success likely, but exact impacts unknown • Shifts in species composition (e.g., potential increase in annual species and warm-adapted species, decline in cold-adapted species) • Earlier flowering and growth phenologies; potential recruitment failure and population decline of species unable to shift phenology (both plants and pollinators), and potential increase in plant-pollinator phenological mismatches	

Heat waves

Heat waves can exacerbate the impacts of warming air temperatures, such as causing an earlier start to the growing season by accelerating snowmelt (Jolly et al. 2005). For example, in the Swiss Alps, a heat wave event caused a 12% increase in the length of an alpine plant growing season by increasing the number of snow-free days (Jolly et al. 2005).

Heat waves may also alter germination patterns, particularly if they occur simultaneously with other extreme events such as drought. For example, Orsenigo et al. (2015) found that heat waves significantly shifted germination phenology of alpine plants in Italy, causing seeds to germinate in fall rather than spring, which then exposed seedlings to cold winter temperatures. Orsenigo et al. (2015) also found that heat waves in combination with drought events resulted in decreased germination in all alpine species.

[3] 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.

Regional Heat Wave Trends	
Historical & current trends: • 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)	*Projected future trends:* • 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)
Summary of Potential Impacts on Habitat *(see text for citations)*	
• Earlier growing season initiation • Enhanced moisture stress in late-summer • Altered seedling germination phenology • Potential decreases in germination if paired with drought events	

Snowpack amount

Snowpack plays a critical role in the distribution, composition, productivity, and survival of alpine grassland and shrubland vegetation. Snowpack deposition patterns control the distribution of alpine vegetation by acting as a major moisture source in an otherwise arid environment (Bishop 2010), and local snow accumulation and snowmelt timing control species composition and productivity (Rundel & Millar 2016). Snow also influences plant distribution and survival by insulating alpine vegetation in the winter, providing protection from wind desiccation and extreme cold (Bishop 2010). Snowpack reductions may increase plant mortality or injury (Bishop 2010). For example, near complete absence of snowpack in the 2015–2016 winter contributed to significant alpine plant dieback and damage (Vuln. Assessment Reviewers, pers. comm., 2018).

Reduced snowpack will limit the amount of snowmelt moisture provided to alpine grasslands and shrublands, which in the absence of summer precipitation, will enhance summer drought stress, limiting productivity and affecting community composition and species diversity (Copeland et al. 2016; Rundel & Millar 2016; Giménez-Benavides et al. 2018). Additionally, changes in snowpack deposition patterns will affect the landscape distribution of alpine plant species (Bishop 2010). For example, areas adjacent to snowbanks that persist into late spring (e.g., on north-facing slopes) typically support the most mesic alpine grassland and shrubland plant types; reduced snowpack, particularly the loss of long-lasting snowbanks, may further limit the distribution of mesic-associated species in alpine environments (e.g., grasses, sedges, shrubs) and favor shifts to more dry-adapted species (e.g., mats, cushions; Rundel & Millar 2016). Additionally, longer snow-free growing seasons caused by reduced snowpack may increase opportunities for encroachment by subalpine tree species and exotic species (Taylor 1995; Cavieres et al. 2005; Rundel & Keeley 2016).

Although trends generally project significant reductions in snowpack by the end of the century (Flint et al. 2013; Thorne et al. 2015), changes in snowpack amount will also exhibit interannual and interdecadal variability as a result of ENSO and PDO cycles. La Niña periods typically translate to cool, dry winters in northern California, contributing to record low snow years. Comparatively, El Niño conditions bring wetter conditions, but the amount of snowfall can still be limited by overall warmer temperatures (Rundel & Millar 2016).

Regional Snowpack Trends	
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)	*Projected future trends:* • 72–94% decrease in April 1 SWE in the Klamath Mountains and 61–89% decrease in the Southern Cascades by 2100 (compared to 1951–1980; Flint et al. 2013; Flint & Flint 2014)
Summary of Potential Impacts on Habitat *(see text for citations)*	
• Restricted distributions of mesic species and/or shifts to more dry-adapted species • Declining productivity as reduced snowmelt inputs enhance summer drought stress • Enhanced winter mortality or damage from wind desiccation or cold exposure due to reduced snow insulation • More snow-free days, potentially increasing establishment of lower-elevation and/or invasive species	

Timing of snowmelt and runoff

Snowmelt patterns control alpine community composition and productivity by influencing water availability and the length of the growing season (Rundel & Millar 2016). Earlier snowmelt timing will lengthen snow-free growing periods, potentially enhancing growth and flowering opportunities for alpine species (Rundel & Millar 2016). However, earlier snowmelt and associated earlier flower and leaf budding may increase alpine plant exposure to frost damage or mortality, particularly if frost event timing does not change in tandem with snowmelt patterns (Inouye 2008). Flower damage from frost can reduce seed production, potentially limiting future recruitment opportunities, and can also reduce resources available to local pollinators (Inouye 2008). Earlier snowmelt may also reduce the amount of moisture available in late summer, enhancing plant vulnerability to desiccation (Benson 1988). Earlier snowmelt may also create more favorable growing conditions for lower-elevation species, including subalpine conifers and invasive vegetation (Taylor 1995; Rundel & Keeley 2016). This could reduce the competitive advantage of alpine species and/or shrink alpine grassland and shrubland area (Rundel & Millar 2016).

Regional Snowmelt Trends	
Historical & current trends: • 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:* • 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)

Regional Snowmelt Trends
Summary of Potential Impacts on Habitat *(see text for citations)*
• Earlier growth but increased late-season moisture stress due to longer snow-free growing season • Possible increased vulnerability to spring frost damage or mortality without snow insulation • May create more favorable growing conditions for lower-elevation vegetation or exotic species

Precipitation amount and timing and drought

Alpine grassland and shrubland community composition is highly influenced by California's Mediterranean climate, receiving winter precipitation in the form of snow followed by summer drought (Rundel & Millar 2016). However, alpine plant recruitment is correlated with rare summer (i.e., growing season) precipitation events, as well as spring runoff in some areas (Wenk & Dawson 2007). Shifts in precipitation amount, timing, and duration will alter moisture availability, potentially altering recruitment patterns and driving shifts in community composition and species diversity (Taylor 1995; Wenk & Dawson 2007; Crimmins et al. 2011; Copeland et al. 2016; Rundel & Millar 2016). For example, higher elevation grasslands in northern California experienced declines in species richness during the 2013–2014 severe drought as a result of reduced snowpack and moisture inputs (Copeland et al. 2016). Declines in growing season precipitation could also reduce already episodic alpine plant germination events (Wenk & Dawson 2007), and when paired with enhanced evaporative demand as a result of warmer air temperatures, could enhance the dominance of species with more rapid onset of germination while suppressing species that require prolonged mesic conditions for germination (Wenk & Dawson 2007). Alternatively, above-average precipitation, particularly precipitation falling during the growing season, may stimulate germination of dormant alpine plant seedbanks (Wenk & Dawson 2007) and/or facilitate downslope expansions of alpine vegetation by increasing climatic water availability (Crimmins et al. 2011). However, more precipitation could also facilitate upward encroachment of subalpine conifer species such as mountain hemlock (Taylor 1995).

Alpine grassland and shrublands are adapted to seasonal summer drought characteristic of Mediterranean climates, which limits alpine community productivity by shortening the length of the growing season (Rundel & Millar 2016). However, alpine grasslands and shrublands may not be as resilient to increasing drought severity and frequency, which may reduce community productivity and recruitment and increase mortality (Giménez-Benavides et al. 2007; Orsenigo et al. 2015), potentially resetting succession (Martin 2001). However, extended drought periods may also expand alpine habitat area by causing a lowering of the treeline (Martin 2001).

Regional Precipitation & Drought Trends	
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)	*Projected future trends:* • 19% decrease to 27% increase in mean annual precipitation by 2100 (compared to 1951–1980) for the Klamath Mountain and Southern

Regional Precipitation & Drought Trends	
• 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)	Cascade ecoregions (Flint et al. 2013; Flint & Flint 2014)[4] • 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) • 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) • 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 Habitat *(see text for citations)*
• Altered community composition; drier conditions may favor species with rapid germination onset life histories • Reduced growing season precipitation may limit germination events • Increased growing season precipitation may increase germination events and/or facilitate conifer encroachment • Enhanced drought conditions may limit plant productivity, recruitment, and survival • Prolonged drought may expand habitat area by causing tree mortality

Soil moisture and climatic water deficit

Soil moisture strongly controls alpine grassland and shrubland recruitment, community composition, cover, and productivity (Benson 1988; Wenk & Dawson 2007; Rundel & Millar 2016). In alpine habitats, soil moisture is largely derived from snowmelt; reduced snowpack and earlier snowmelt timing, as well as altered precipitation patterns and increased drought, are likely to reduce soil moisture availability, particularly in mid- to late-summer (Benson 1988; Rundel & Millar 2016). Reduced soil moisture may limit plant growth (Walker et al. 1995), recruitment (Wenk & Dawson 2007; Orsenigo et al. 2015), and distribution, which will likely drive shifts in alpine grassland and shrubland community composition (Wenk & Dawson 2007; Rundel & Millar 2016).

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

Alpine grasslands and shrublands will also be affected by increasing climatic water deficit. 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).[5] Increased evaporative demand as a result of warmer air temperatures is likely to drive increased CWD, regardless of changes in precipitation (Thorne et al. 2015). Enhanced CWD will change environmental water balances in alpine areas (Stephenson 1998), effectively enhancing summer drought stress and causing an earlier end to the growing season (Rundel & Millar 2016). Annual herbaceous plants are likely to be more impacted by these changes than perennial species, which feature adaptations to dry conditions (e.g., heathers with leathery or spindly foliage that prevent rapid water loss; Vuln. Assessment Reviewers, pers. comm., 2018).

<table>
<tr><th colspan="2">Regional Climatic Water Deficit (CWD) & Soil Moisture Trends</th></tr>
<tr><td>Historical & current trends:
• 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)
• No trends available for soil moisture</td><td>Projected future trends:
• 10–32% increase in average annual CWD in the Klamath Mountains and 16–43% increase in the Southern Cascades by 2100 (compared to 1951–1980; Flint et al. 2013; Flint & Flint 2014)
• 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)</td></tr>
<tr><th colspan="2">Summary of Potential Impacts on Habitat (see text for citations)</th></tr>
<tr><td colspan="2">• Reduced plant growth and recruitment
• Altered species composition and landscape distribution</td></tr>
</table>

Sensitivity and future exposure to changes in natural disturbance regimes

Regional experts evaluated alpine grasslands and shrublands as having high sensitivity to changes in natural disturbance regimes (moderate confidence in evaluation), with overall low-moderate future exposure to these stressors within the study region (moderate confidence). Key natural disturbance regimes that affect alpine grasslands and shrublands include wildfire and volcanic events.

[5] CWD, 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).

Wildfire

Wildfire is infrequent in alpine grasslands and shrublands due to low fuel availability (Cansler et al. 2017).[6] Most fires result from ignition and fire spread from lower elevations rather than ignition in the alpine zone (Vuln. Assessment Reviewers, pers. comm., 2018). While the likelihood of future natural ignitions (i.e., lightning strikes) is uncertain, increasing human populations and expansion of the wildland urban interface will likely increase risk of human-ignited wildfires across the region (Mann et al. 2016; Balch et al. 2017). Simultaneously, earlier snowmelt and warmer temperature may increase the frequency, intensity, and size of fires in adjacent subalpine areas (Schwartz et al. 2015; Westerling 2016), increasing the risk of fire spread to alpine zones if sufficient fuel is available (Cansler et al. 2017). Fires can cause local extirpations of alpine species (Cansler et al. 2017), and alpine areas are generally slow to recover from such disturbances (Benson 1988).

Changing wildfire regimes may also impact alpine vegetation distribution (Cansler et al. 2017). For example, wildfires in subalpine areas may temporarily create downslope colonization opportunities for alpine vegetation (albeit with competition), which may temporarily combat alpine habitat loss to lower-elevation species' encroachment (Martin 2001; Rundel & Millar 2016; Cansler et al. 2017). Conversely, with warming temperatures, fire could facilitate upward tree movement by removing alpine vegetation and providing new growing areas for lower-elevation species (Cansler et al. 2017). Wildfire can also alter snow deposition, avalanche patterns, and site albedo by removing trees and other vegetation, affecting local alpine grassland and shrubland distribution (Cansler et al. 2017; Vuln. Assessment Reviewers, pers. comm., 2018).

Regional Wildfire Trends[7]	
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)	*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) • Little projected change in fire severity in northwestern California by 2050 in models based solely on historical fire-climate relationships (Parks et al. 2016)

[6] Tribal groups traditionally used somewhat frequent low severity burns in higher elevation areas (e.g., meadows) to maintain productivity of culturally important species (e.g., huckleberry, beargrass; Turner et al. 2011; Norgaard et al. 2016). However, cultural burning typically occurred in a matrix with other vegetation types below treeline, not in alpine grasslands and shrublands (Vuln. Assessment Reviewers, pers. comm., 2018).

[7] This information represents regional trends across all habitat types and elevations. No wildfire trend information specific to areas above treeline is available.

Regional Wildfire Trends[7]	

• 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 trends in northern California fire severity that include data from the last ten years
	○ 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 Habitat *(see text for citations)*
• Many alpine areas are not vulnerable to fire due to low and patchy fuel availability • In areas with available fuel, fire may cause localized extirpation of alpine species, and habitat will be slow to recover • Fire can alter alpine vegetation distribution: may create downslope colonization opportunities and/or exacerbate upslope habitat contraction • Removal of existing trees and vegetation will alter snow deposition, avalanche patterns, and site albedo, influencing alpine vegetation distribution

Volcanic events

Volcanic activity leading to landslides or mass-wasting events can temporarily eliminate alpine vegetation or reset succession (Benson 1988). However, only some alpine grasslands and shrublands occur in volcanic areas (e.g., southern Cascades). Significant volcanic activity is quite rare, and therefore, regional alpine habitat exposure to volcanic activity is limited (Vuln. Assessment Workshop and Reviewers, pers. comm., 2017 and 2018).

Sensitivity and current exposure to non-climate stressors

Regional experts evaluated alpine grasslands and shrublands as having low sensitivity to non-climate stressors (moderate confidence in evaluation), with an overall low current exposure to these stressors within the study region (moderate confidence). Key non-climate stressors that affect alpine grasslands and shrublands include invasive and other problematic species, recreation, and trails.[8]

Invasive and problematic species

Due to harsh environmental conditions, alpine grassland and shrubland communities have experienced limited successful invasion by exotic species (Rundel & Millar 2016). However, exotic species establishment may become more frequent if alpine growing conditions become more favorable under changing climate conditions (e.g., warming temperatures, increased water availability; Cavieres et al. 2005; Rundel & Keeley 2016; Giménez-Benavides et al. 2018; Lembrechts et al. 2018), particularly if introduction vectors are not controlled (e.g., recreation, grazing; Rundel & Millar 2016). Exotic perennial herbs (e.g., dandelion [*Taraxacum officinale*], sheep sorrel [*Rumex acetosella*], Dyers woad [*Isatis tinctoria*]) and perennial grasses (e.g., timothy [*Phleum pratense*], redtop [*Agrostis stolonifera*], Kentucky bluegrass [*Poa pratensis*]) likely pose the most serious threat to native alpine communities, as perennial life histories have proven the most successful in these extreme growing conditions (Rundel & Keeley 2016; Vuln. Assessment Reviewers, pers. comm., 2018). Increased exotic species establishment and abundance would increase competition with native taxa for already limited resources (e.g., soil moisture; Rundel & Keeley 2016) and alter existing ecological relationships (e.g., insect pollination; Cavieres et al. 2005; Muñoz & Cavieres 2008; Giménez-Benavides et al. 2018).

Recreation and trails

Due to their remote locations, alpine grasslands and shrublands have experienced limited human disturbance (Rundel & Millar 2016). However, localized recreation and trail use (e.g., mountain biking, hiking, peak bagging, pack animals) exist in some alpine areas within northern California (Vuln. Assessment Workshop, pers. comm., 2017). Relative to other habitats, alpine areas may be disproportionally affected by existing and increasing recreational pressure due to their small size, sensitivity to disturbance, and proximity to peaks (Vuln. Assessment Reviewers, pers. comm., 2018). Recreational activities contribute to erosion, increase bare ground (e.g., via social trail formation), trample vegetation and elevate plant mortality, and reset succession, which affects food available for alpine wildlife (e.g., American pika [*Ochotona princeps*]; Benson 1988; Martin 2001; USDA Forest Service 2012; Rundel & Millar 2016). Disturbed conditions associated with trail and recreational use may also provide establishment opportunities for invasive vegetation (Parks et al. 2005), and recreational users and their associated equipment may serve as introduction vectors for exotic species (Anderson et al. 2015).

Adaptive Capacity

Alpine grasslands and shrublands were evaluated by regional experts as having low-moderate overall adaptive capacity (moderate confidence in evaluation).

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[8] These non-climate stressors were ranked as a having only a low or low-moderate impact on this habitat type.

Habitat extent, integrity, continuity, and permeability

Regional experts evaluated alpine grasslands and shrublands as having a low geographic extent (high confidence in evaluation), moderate structural and functional integrity (moderate confidence), and low-moderate continuity (high confidence). Landscape permeability for alpine grasslands and shrublands was evaluated as low-moderate (high confidence). Elevation was identified as the primary barrier to habitat continuity and dispersal across the study region, as alpine vegetation generally cannot persist at lower elevations.[9]

Alpine grasslands and shrublands areas occupy roughly 506 km^2 across the state of California, with the majority of that area occurring in the Sierra Nevada (Rundel & Millar 2016; Thorne et al. 2016). In northern California, alpine grasslands and shrublands occur in the southern Cascades on Mount Shasta (between 2,286–3,900 m [7,500–12,800 ft]), Lassen Peak (above 2,800 m [9,186 ft]), and in north-facing cirques of Magee Peak (Benson 1988; USDA Forest Service 2012; Rundel & Millar 2016). Alpine grasslands and shrublands can also be found in the highest peaks of the Klamath Mountains (typically above 2,270 m [7,500 ft]), including in the Trinity Alps, Marble Mountains, and Scott Mountains (Benson 1988; Rundel & Millar 2016). Within the Klamath Mountains, alpine vegetation is most extensive in the Trinity Alps, and is largely limited to north-facing aspects, while subalpine conifers, including krummholz individuals, occupy southern slopes (Sawyer & Keeler-Wolf 2007). Alpine communities may extend to elevations as low as 2,000 m (6,561 ft) on karst topography in the Marble Mountains, and serpentine soils allow persistence of lower-elevation alpine vegetation communities in some areas (Rundel & Millar 2016).

Alpine grassland and shrublands generally function as island ecosystems, isolated from other similar habitat types (Martin 2001; Giménez-Benavides et al. 2018). Some habitat areas are completely isolated (e.g., mountain tops), while others are more continuous (Vuln. Assessment Workshop, pers. comm., 2017). Current location at the highest regional elevations leaves little opportunity for these habitats to migrate in response to changing climatic conditions (California Climate Change Center 2006; Carroll et al. 2015). Alpine habitat vulnerability to climate-driven species extinctions will be highest in areas with the least amount of current alpine area above treeline, and in areas with the narrowest elevation gradients (Giménez-Benavides et al. 2018).

Due to their remote locations, alpine grasslands and shrublands experience less human impacts than other habitats (Rundel & Millar 2016). Additionally, a majority of alpine grasslands and shrublands occur in areas designated as Wilderness (e.g., Mt. Shasta, Trinity Alps, Marble Mountains), which limits some human impacts (Vuln. Assessment Reviewers, pers. comm., 2018).[10] However, alpine grasslands and shrublands are highly sensitive to disturbance that does occur (Martin 2001). For example, alpine grassland and shrubland integrity still exhibits

[9] Barriers presented are those ranked as having a moderate or higher impact on this habitat type; an additional barrier that may limit habitat continuity and dispersal to a lesser degree is active volcanism.

[10] Alpine areas not protected by wilderness designations include areas east of Interstate 5 in Siskiyou County (e.g., Goosenest Mountain and other local buttes), Mt. Eddy and the Eddys subrange, and the Scott Mountains subrange.

legacy sheep grazing effects (Vuln. Assessment Workshop, pers. comm., 2017). Impacts are particularly acute in alpine meadow riparian zones, where cattle grazing has reduced native grass species abundance and streambank stability (Cook et al. 2014). Historic sheep grazing has also caused the creation of barrens in the Klamath Mountains (e.g., along the Siskiyou Crest at the California/Oregon border; Sawyer & Keeler-Wolf 2007; Vuln. Assessment Reviewers, pers. comm., 2018).

Habitat diversity

Regional experts evaluated alpine grasslands and shrublands as having moderate-high physical and topographical diversity (high confidence in evaluation), moderate-high component species diversity (high confidence), and moderate functional group diversity (moderate confidence).

Alpine grasslands and shrublands exhibit variable topography, wind exposure, substrate type, soil depth and drainage, and snow accumulation (Rundel & Millar 2016). This physical and topographic diversity creates highly variable moisture and temperature regimes, which drives high spatial heterogeneity in alpine vegetation assemblages (Martin 2001; Thorne et al. 2016). For example, vegetation assemblages on wind-swept ridges are typically comprised of cold- and drought-hardy cushion and mat species, while dwarf shrub species are restricted to more wind-protected and mesic sites such as drainage courses (Rundel & Millar 2016).

Two main functional groups are present in alpine grasslands and shrublands: herbaceous perennial species and dwarf or prostrate shrubs. Herbaceous perennials represent the dominant cover type, with broad-leaved herbaceous perennial species being most common, followed by graminoids, mats and cushions, and sometimes, geophytes (Sawyer & Keeler-Wolf 2007; Rundel & Millar 2016). Short growing seasons limit the success of annual life history strategies in this habitat, although some herbaceous annuals can be present (Rundel & Millar 2016). Shrubs are present in the form of sub-shrubs with little woody plant growth. The shrub functional group typically exhibits lower species richness than herbaceous perennials (Sawyer & Keeler-Wolf 2007; Rundel & Millar 2016). Across the study region, herbaceous and shrub species composition at the site level is highly variable (Sawyer & Keeler-Wolf 2007; USDA Forest Service 2009a, 2009b).[11] Species and functional group diversity are also enhanced by soil crusts with lichens, mosses, and bacteria (Vuln. Assessment Workshop, pers. comm., 2017), by krummholz forms of coniferous trees such as whitebark pine (*Pinus albicaulis*) (USDA Forest Service 2012), and by serpentine soils at high elevations that support rare and endemic species (e.g., Trinity buckwheat [*Eriogonum alpinum*], Siskiyou milkvetch [*Astragalus whitneyi* var. *siskiyouensis*]; Calflora 2019).

Some alpine grassland and shrubland species also exist at lower elevations, and may be less vulnerable to climate-driven habitat reductions. Comparatively, species limited to high elevations, and particularly high-elevation endemic species, are more vulnerable to extirpation as climate change shrinks available alpine habitat. Known alpine endemic species include

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[11] See Sawyer & Keeler-Wolf (2007) and USDA Forest Service (2009a, 2009b) for descriptions of vegetation assemblages in different alpine areas of the study region.

Heller's Mount Eddy lupine (*Lupinus lapidicola*), Stebbins' lewisia (*Lewisia stebbinsii*; Sawyer 2007), Shasta sky pilot (*Polemonium pulcherrimum var. shastensis*), Mt. Shasta arnica (*Arnica viscosa*; USDA Forest Service 2012), Mt. Eddy sky pilot (*Polemonium eddyense*), crested cinquefoil (*Potentilla cristae*), Sawyer's pussy-toes (*Antennaria sawyeri*), Cascade alpine campion (*Silene suksdorfii*), rough harebell (*Campanula scabrella*), Trinity buckwheat, dwarf alpinegold (*Hulsea nana*), Mt. Eddy buckwheat (*Eriogonum umbellatum* var. *humistratum*), and Howell's tauschia (*Tauschia howellii*; Vuln. Assessment Reviewers, pers. comm., 2018).

Alpine grasslands and shrublands support a variety of wildlife, including alpine specialists and species from lower elevations that utilize alpine areas transiently or seasonally. Similar to plant vulnerability, alpine specialist wildlife will be most vulnerable to climate-induced habitat alterations. Alpine specialists in the southern Cascades include American pika, yellow-bellied marmots (*Marmota flaviventris*), gray-crowned rosy finch (*Leucosticte tephrocotis*; USDA Forest Service 2012; Rundel & Millar 2016) and Clark's nutcracker (*Nucifraga columbiana*; Vuln. Assessment Reviewers, pers. comm., 2018). Alpine habitats are also used seasonally by several species designated as Species of Greatest Conservation Need by the California Department of Fish and Wildlife, including the northern goshawk (*Accipiter gentilis*), golden eagle (*Aquila chrysaetos*), Sierra Nevada red fox (*Vulpes vulpes necator*), and Pacific marten (*Martes caurina*; CDFW 2015).

Resistance and recovery

Regional experts evaluated alpine grasslands and shrublands as having low resistance to climate stressors and natural disturbance regimes (moderate confidence in evaluation). Recovery potential was evaluated as low (moderate confidence).

Alpine grassland and shrubland species are adapted to extreme abiotic conditions. Common plant adaptations to the alpine environment include small size, low height, compact form, and higher allocation of biomass to below-ground versus above-ground structures. These characteristics help minimize air flow cooling and facilitate heat absorption from the sun as well as heat transmission to the ground to warm roots, effectively creating more moderate microclimates than surrounding barren areas (Bishop 2010; Rundel & Millar 2016). Additionally, many alpine plants benefit from plant-plant interactions (e.g., nurse plants) that further buffer harsh environmental conditions and bolster plant performance and survival (Giménez-Benavides et al. 2018).

Despite being long-lived, alpine grassland and shrubland species are not very resilient to disturbance, or to changes in climate that increase competition or create more severe conditions (Rundel & Millar 2016; Rundel & Keeley 2016; Lembrechts et al. 2018). Alpine communities are slow to recover from disturbance, exhibiting slow successional processes (Benson 1988). For example, mountain heather recovery can take several hundred years following disturbance (USDA Forest Service 2012). Some alpine vegetation is more resilient to disturbance (e.g., sedge turfs; Martin 2001). Alpine vegetation is also not very resilient to climate-induced increases in competition (e.g., air temperature increases facilitating tree encroachment or upward expansion of exotic species; Rundel & Millar 2016; Rundel & Keeley 2016; Lembrechts et al. 2018) or to climate-driven changes that create more severe environmental conditions (e.g., snowpack loss and/or earlier snowmelt reducing winter and/or spring frost insulation; Inouye 2008; Bishop 2010). However, high topographic and substrate diversity in alpine areas may create localized conditions that function as climatic refugia and confer resilience to invasion from lower-elevation species (Skinner et al. 2006; Sawyer & Keeler-Wolf 2007; Rundel & Millar 2016; Kulonen et al. 2017; Giménez-Benavides et al. 2018), although alpine vegetation must be able to migrate and establish locally for these microsites to buffer climate impacts (Rundel & Millar 2016).

Management potential

Public and societal value

Regional experts evaluated alpine grasslands and shrublands as having moderate-high public and societal value (moderate confidence in evaluation).

There is some societal appreciation for and attraction to flowering alpine areas (Vuln. Assessment Workshop, pers. comm., 2017). Alpine areas are also valued for their spiritual and cultural importance to tribal groups (Turner et al. 2011), and for recreational hiking, camping, and climbing opportunities (USDA Forest Service 2012). Some constituency groups that support alpine grassland and shrubland conservation and management include regional tribes, the Sierra Club, and Friends of the Wilderness (Vuln. Assessment Workshop, pers. comm., 2017). There is some potential that extreme events (e.g., fires, volcanic events) would generate public interest or concern about alpine grassland and shrubland management (Vuln. Assessment Workshop, pers. comm., 2017).

Management capacity and ability to alleviate impacts[12]

Regional experts evaluated the potential for reducing climate impacts on alpine grasslands and shrublands through management actions as low-moderate (moderate confidence in evaluation). Regional experts also identified potential use conflicts and/or competing interests such as recreation and tribal spiritual uses (Vuln. Assessment Workshop, pers. comm., 2017).

Management opportunities in alpine grassland and shrublands will likely involve managing non-climate anthropogenic impacts, as managers have little control over temperature and snowpack trends (Cook et al. 2014). For example, restoring alpine meadows impacted by past grazing by propagating native species and removing invasive vegetation may restore native grass diversity and/or help protect water supply and filtration ecosystem services (Cook et al. 2014). Wilderness management tools, such as limiting the number of people present in alpine areas, may also help moderate the synergistic impacts of climate change and human visitation on vegetation (Vuln. Assessment Reviewers, pers. comm., 2018). However, ecological management can often be at odds with other management objectives (e.g., recreational access, visitor experience; Vuln. Assessment Reviewers, pers. comm., 2018). Managers can also partner

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

with local tribes to best understand and accommodate cultural uses and values in alpine areas (Vuln. Assessment Workshop, pers. comm., 2017).

Ecosystem services

Alpine grasslands and shrublands provide a variety of ecosystem services, including:

- Provisioning of natural medicines and fresh water;
- Regulation of water purification;
- Support of soil formation/retention and 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).

Alpine grassland and shrubland areas play a critical role in collecting and filtering water that supplies lower-elevation habitats and downstream uses (Cook et al. 2014). Snowpack accumulates during the winter, and then percolates through the soil, emerging as streams, seeps, and springs at lower elevations (Cook et al. 2014). Regional management programs target maintaining these fresh water ecosystem services, including restoration of alpine meadows historically degraded by grazing (Cook et al. 2014). Alpine areas are also valued for recreation (e.g., climbing, hiking, horseback riding), and these uses are managed in many areas (USDA Forest Service 2012).

Alpine areas provide a variety of cultural ecosystem services (Turner et al. 2011). These areas hold cultural and spiritual significance, both for their seasonal resource gathering opportunities and for spiritual use, including spiritual training and spirit questing (Turner et al. 2011). Alpine meadows and adjacent subalpine parklands provide important food, medicinal, and fiber resources, and their higher elevation location allows for progressive resource gathering throughout the late spring, summer, and early fall seasons as lower-elevation resources are depleted (Turner et al. 2011). Additionally, stones from alpine areas were also traditionally used to make arrowheads and tools (Turner et al. 2011; Norgaard et al. 2016).

Recommended Citation

Reynier WA, Hilberg LE, Kershner JM. 2019. Alpine Grasslands and Shrublands: 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).

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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),[13] 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.[14]

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

[14] 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

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