Sierra Nevada Ecosystem Vulnerability Assessment Briefing: Alpine/Subalpine

Mountain hemlock (*Tsuga mertensiana*), whitebark pine (*Pinus albicaulis*), western white pine (*P. monticola*), lodgepole pine (*P. contorta*), red fir (*Abies magnifica*), bristlecone pine (*P. longaeva*), limber pine (*P. flexilis*), foxtail pine (*P. balfouriana*).

Background and Key Terminology

This document summarizes the primary factors that influence the vulnerability of a focal resource to climate change over the next century. In this context, vulnerability is a function of the sensitivity of the resource to climate change, its anticipated exposure to those changes, and its capacity to adapt to changes. Specifically, sensitivity is defined as a measure of whether and how a resource is likely to be affected by a given change in climate, or factors driven by climate; exposure is defined as the degree of change in climate or climate-driven factors a resource is likely to experience; and adaptive capacity is defined as the ability of a resource to accommodate or cope with climate change impacts with minimal disruption (Glick et al. 2011). The purpose of this assessment is to inform forest planning by government, non-profit, and private sector partners in the Sierra Nevada region as they work to integrate climate change into their planning documents.

Executive Summary

The overall vulnerability of alpine/subalpine systems is ranked moderate-high, due to its high sensitivity to climate and non-climate stressors, low-moderate adaptive capacity, and moderate exposure.

Alpine/subalpine systems are sensitive to climate-driven changes such as:

- increased temperature,
- decreased water supply (e.g. precipitation and snowpack), and
- increased climatic water deficit.

Alpine/subalpine systems exhibit varying sensitivities to climate and climate-driven changes by species, including changes in temperature, precipitation type and volume, and climatic water deficit. A positive relationship between growth and temperature exists for some species, while for others, elevated temperatures and drought stress have been correlated with mortality events.

Alpine/subalpine systems are also sensitive to several non-climate stressors including:

- development (e.g. ski resorts), and
- insects and disease.

Development of high altitude recreation areas such as ski resorts can degrade and fragment alpine habitat, and create a barrier to uphill shifts in plant and animal communities. The adaptive capacity of alpine systems is strongly constrained by the geographic isolation of alpine zones and limited soil productivity.

Recommended Citation

Hauptfeld, R.S. and J.M. Kershner. 2014. Sierra Nevada Ecosystem Vulnerability Assessment Briefing: Alpine/Subalpine. Version 1.0. EcoAdapt, Bainbridge Island, WA.

This document is available online at EcoAdapt (http://ecoadapt.org/programs/adaptation-consultations/calcc).

Sensitivity & Exposure

Sensitivity to climate and climate-driven changes

Although sensitivities vary by species and growth morphology, alpine/subalpine systems appear to be sensitive to several climate and climate-driven changes, including increased temperature, decreased water supply (e.g. precipitation and snowpack), and increased climatic water deficit. Some studies indicate that responses of high elevation forests may be largely dictated by water supply (Lloyd and Graumlich 1997; Fites-Kaufman et al. 2007), and evidence suggests that warming, plus higher precipitation in some cases, may have improved growing conditions for some tree species in the subalpine zone since the 1930s (Bouldin 1999; Dolanc et al. 2013). For example, despite substantial species to species variation, high winter precipitation combined with warm summers appear to produce maximum growth for foxtail pine, lodgepole pine, and western white pine (Fites-Kaufman et al. 2007) as well as decreased mortality for lodgepole pine, western white pine, and mountain hemlock (Bouldin 1999). A positive relationship exists between temperature in the Sierra Nevada and ring-width growth of treeline bristlecone pine (Salzer et al. 2009), branch growth of whitebark pine and lodgepole pine, and establishment of western white pine (Millar et al. 2004). For near-treeline mountain hemlock forests in Lassen Volcanic Park, warming during the last 150 years is associated with increases in density and population expansion, and peaks in initial recruitment are associated with mesic warm periods between 1886-1915 (Taylor 1995). Similarly, recruitment of mountain hemlock is retarded in areas with high snowpack and with late laying snow (Taylor 1995), suggesting mountain hemlock may benefit where snowpack decreases and snowmelt occurs earlier.

Although steady or increased precipitation and warming temperatures have led to less stressful conditions for recruitment and survival of small trees, these changes may also contribute to increased mortality of large subalpine trees (Dolanc et al. 2013). For example, whitebark pine experienced significant mortality from 2007-2010 in Sierra Nevada subalpine sites (mean elevation 2993 m)(9820 ft) that were warmer and drier relative to species distribution (Millar et al. 2004). Foxtail pines in drier regions of the cold and dry eastern crest of Sequoia National Park may lose the ability to grow in warmer temperatures if insufficient water leads to drought stress (Bunn et al. 2005). The paleoecological record suggests that future warming is unlikely to cause an expansion of subalpine extent if accompanied by a reduction in water supply (Lloyd and Graumlich 1997).

In addition, rising temperatures between 1987-2007 indicates 73% of ‘Köppen’ alpine tundra classification in the western United States now exceeds the 10°C (50˚F) temperature threshold for this habitat classification during in the warmest month (Diaz and Eischeid 2007). Our understanding of limiting factors such as temperature means and extremes, and moisture availability in species establishment and survival in alpine habitats remains poor (Graham et al. 2012).

Future climate exposure

Important climate and climate-driven factors to consider for alpine/subalpine systems include changes in temperature, timing and volume of precipitation and snowpack, and climatic water deficit.

Many models of climate change in the Sierra Nevada predict uphill migration and restricted distribution of alpine/subalpine plant communities (Hayhoe et al. 2004; Lenihan et al. 2006; Van de Ven et al. 2007). Hayhoe et al. (2004) predicted 70-95% loss of alpine/subalpine forest relative to 1961-1990 stands due to limited space for vertical migration, and in the three scenarios modeled by Lenihan et al. (2006) to the end of the century, the greatest declines in alpine/subalpine forest extent correspond to the warmest conditions. Van de Ven et al. (2007) modeled predicted distributions of 14 alpine and subalpine species in the (arid) White and Inyo Mountains under temperature increases of 6°C, in 1° increments. Models predict all species to shift upslope and decrease in range, with some species predicted to shift from south to north facing slopes, and experience fragmentation. Under a 3°C (5.4°F) increase, two species became locally extinct; under a 6°C (10.8° F) increase, 10 out of 14 species disappeared from the study area.

In contrast, Millar et al. (2006) find that climatic conditions projected for 2070-2099 in Whitewing Mountain and San Joaquin, Mono County are similar to Medieval climatic conditions, which produced a significant increase in subalpine forest extent and diversity, in contrast to the large estimated reduction of subalpine forest projected based on vegetation-climate projections.

Moreover, data on alpine microclimate traits suggest that models predicting upslope shifts of species under increasing temperatures may not be entirely realistic, and that microclimate heterogeneity may slow such migration. Large and persistent microhabitat temperature variations over mesoscale alpine landscapes may mimic temperature gradients of several hundred meters of elevation, suggesting that alpine plants may find appropriate thermal niches for establishment and survival without elevational shifts (Scherrer and Körner 2011; Graham et al. 2012). Graham et al. (2012) found that alpine fellfield topographic variability in the White Mountains, California created thermal microhabitat conditions at a scale of centimeters, due to the presence of low-lying plants, which transpire and shade the soil surface. Fellfield habitats may offer significant buffering from climate warming because the temperature differences are greater than the range of warming scenarios over the next century in IPCC projections.

Temperature: High elevation forests have seen pronounced increases in temperature over the past century (Dolanc et al. 2013). Over the next century, annual temperatures in the Sierra Nevada are expected to rise between 2.4-3.4˚C varying by season, geographic region, and elevation (Das et al. 2011; Geos Institute 2013). On average, summer temperatures are expected to rise more than winter temperatures throughout the Sierra Nevada region (Hayhoe et al. 2004; Cayan et al. 2008), with changes of least magnitude during both seasons anticipated in the central bioregion (Geos Institute 2013). Associated with rising temperatures will be an increase in potential evaporation (Seager et al. 2007).

Precipitation: Precipitation has increased slightly (~2%) in the Sierra Nevada over the past 30 years compared with a mid-twentieth century baseline (1951-1980) (Flint et al. 2013), and in upper elevation forests of the central Sierra Nevada, average precipitation increased from 41.7 cm to 63.2 cm from the decade 1910-1920 to 1990-2000 (Millar et al. 2004). Projections for future precipitation in the Sierra Nevada vary among models; in general, annual precipitation is projected to exhibit only modest changes by the end of the century (Hayhoe et al. 2004; Dettinger 2005; Maurer 2007; Cayan et al. 2008), with decreases in summer and fall (Geos Institute 2013). Frequency of extreme precipitation, however, is expected to increase in the Sierra Nevada between 18-55% by the end of the century (Das et al. 2011).

Snow volume and timing: Despite modest projected changes in overall precipitation, models of the Sierra Nevada region largely project decreasing snowpack and earlier timing of runoff (Miller et al. 2003; Dettinger et al. 2004b; Hayhoe et al. 2004; Knowles and Cayan 2004; Maurer 2007; Maurer et al. 2007; Young et al. 2009), as a consequence of early snowmelt events and a greater percentage of precipitation falling as rain rather than snow (Dettinger et al. 2004a, 2004 b; Young et al. 2009; Null et al. 2010). Annual snowpack in the Sierra Nevada is projected to decrease between 64-87% by late century (Thorne et al. 2012; Flint et al. 2013), with declines of 10-25% above 3750 m (12303 ft), and 70-90% below 2000 m (6562 ft) (Young et al. 2009). The greatest declines in snowpack are anticipated for the northern Sierra Nevada (Safford et al. 2012), with current pattern of snowpack retention in the higher-elevation southern Sierra Nevada basins expected to continue through the end of the century (Maurer 2007). The greatest losses in snowmelt volume are projected between 1750 m to 2750 m (5741 ft to 9022 ft) (Miller et al. 2003; Knowles and Cayan 2004; Maurer 2007; Young et al. 2009).

Snow provides an important contribution to spring and summer soil moisture in the western U.S. (Sheffield et al. 2004), and earlier snowmelt can lead to an earlier, longer dry season (Westerling et al. 2006). A shift from snowfall to rainfall is also expected to result in flashier runoff with higher flow magnitudes, and may result in less water stored within watersheds, decreasing meal annual flow (Null et al. 2010). Mean annual flow is projected to decrease most substantially in the northern bioregion (Null et al. 2010).

Climatic water deficit: Climatic water deficit, which combines the effects of temperature and rainfall to estimate site-specific soil moisture, is a function of actual evapotranspiration and potential evapotranspiration. Increases in potential evapotranspiration will likely be the dominant influence in future hydrologic cycles in the Sierra Nevada, decreasing runoff even under forecasts of increased precipitation, and driving increased climatic water deficits (Thorne et al. 2012). In the Sierra Nevada, climatic water deficit has increased slightly (~4%) in the past 30 years compared with the 1951-1980 baseline (Flint et al. 2013). Future downscaled water deficit modeling using the Basin Characterization Model predicts increased water deficits (i.e., decreased soil moisture) by up to 44%, with the greatest increases in the northern Sierra Nevada (Thorne et al. 2012; Flint et al. 2013; Geos Institute 2013).

Wildfire: Historically, forest fires were relatively rare in alpine and subalpine vegetation, and did not play as strong a role in structuring these ecosystems as they did in lower elevation systems (Van de Water and Safford 2011; Safford and Van de Water 2013). However, with earlier snowmelt and warmer temperatures, models and current trends suggest that fire may become a more significant ecological disturbance in high elevation forests through the 21st century (Fites-Kaufman et al. 2007; Mallek et al. 2013), especially if climate warming leads to densification of bristlecone stands (Dolanc et al. 2013b). Both the frequency and annual area burned by wildfires in the western U.S. have increased strongly over the last several decades (Westerling et al. 2006). Fire severity in the Sierra Nevada also rose from 17% to 34% high-severity (i.e. stand replacing) fire, especially in middle elevation conifer forests (Miller et al. 2009). In the Sierra Nevada, increases in large fire extent have been correlated with increasing temperatures and earlier snowmelt (Westerling and Bryant 2006), as well as current year drought combined with antecedent wet years (Taylor and Beaty 2005). Occurrence of large fire and total area burned in California are predicted to continue increasing over the next century, with total area burned increasing by up to 74% by 2085 (Westerling et al. 2011). The area burned by wildfire in the Sierra Nevada is projected to increase between 35-169% by the end of the century, varying by bioregion, with the greatest increases projected at mid-elevation sites along the west side of the range (Westerling et al. 2011; Geos Institute 2013). Wildfire would be expected to have greatest impact in denser stands and at lower elevations adjacent to relatively productive upper montane forests, where fuel loading is higher and spatially contiguous.

More information on downscaled projected climate changes for the Sierra Nevada region is available in a separate report entitled *Future Climate, Wildfire, Hydrology, and Vegetation Projections for the Sierra Nevada, California: A climate change synthesis in support of the Vulnerability Assessment/Adaptation Strategy process* (Geos Institute 2013). Additional material on climate trends for the system may be found through the TACCIMO website (http://www.sgcp.ncsu.edu:8090/). Downscaled climate projections available through the Data Basin website (http://databasin.org/galleries/602b58f9bbd44dffb487a04a1c5c0f52).

Sensitivity to non-climate stressors

Alpine/subalpine systems are sensitive to non-climate stressors, including insects and disease, and development of high-elevation recreation areas, such as ski resorts. Mountain pine beetle and whitebark pine beetle infestations have resulted in major mortality events for subalpine species, such as whitebark pine and limber pine in recent decades in western North America (Logan and Powell 2001, Logan et al. 2010 cited in Millar et al. 2012). In whitebark pine forests, significant ongoing mortality is also caused by white pine blister rust (*Cronartium ribicola* A. Dietr.) (Tomback and Achuff 2010 cited in Millar et al. 2012). Rising minimum temperatures, combined with drought, contribute to bark beetle infestations in the Sierra Nevada (Millar et al. 2007 cited in Millar et al. 2012), and can aggravate climate-driven mortality.

Development of high elevation recreation area such as ski resorts can degrade and fragment alpine habitat, and create a barrier to uphill shifts in plant and animal communities. However, commercial development is limited in extent and its overall impact may be low.

Adaptive Capacity

The adaptive capacity of alpine/subalpine systems is largely constrained by the limited opportunity for expansion and vertical migration (Hayhoe et al. 2004), slow establishment and recovery. The region south of Lake Tahoe exhibits consistent but limited alpine and fairly continuous subalpine coverage. In comparison, the alpine system in the northern Sierra Nevada is found in isolated mountain peaks. Species differ between the eastern and western slopes, although they are consistent between alpine zones in the southern and northern parts of the state. For bristlecone pine, habitat availability at higher elevations in the White and Inyo mountains may be limited by its aversion to granitic substrates. Adequate carbonate substrates at high enough elevations may not be available under increases of 5°C (9° F) (Van de Ven et al. 2007).

However, some alpine and subalpine species display characteristics that that may enhance adaptive capacity. For example, the limber pine appears to be relatively drought resistant (compared with whitebark pine) and may also have higher genetic diversity, allowing for adaptation to drought conditions (Millar et al. 2010). The foxtail pine also displays characteristics that reduce moisture and nutrient requirement (Bunn et al. 2005), and mountain hemlock tree patches may change the microclimate, improving mountain hemlock recruitment despite unfavorable climatic conditions (Taylor 1995).

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