



CalVeg types included: **SCN**: Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), mountain hemlock (*Tsuga mertensiana*)

Sensitivity Assessment

1. Direct sensitivities to changes in temperature and precipitation

- Temperature
 - Means and extremes
 - Historical
 - High elevation temperatures tend to be cool year round with an average ranging from -11.5 – 1.5°C (11-35°F) in January and 5.5 – 19.5°C (42-67°F) in July. Over the past century, high elevation forests have seen pronounced increases in temperature. In the Central Sierra Nevada, daily minimum temperature has increased by 1.2°C since 1929-34 (Dolanc, 2012). From 1910-20, average minimum temperature was 3.8°C; in 1990-2000, average minimum temperature increased to 7.5°C in upper elevation forests of the central Sierra Nevada (Millar et al., 2004).
 - Future
 - Over the next century, average temperatures across California are expected to increase by 2-4°F in winter and 4-8°F in the summer. Models indicate that there may be less warming along the southwest coast but more warming to the north and northeast (Hayhoe et al., 2004).
 - System's sensitivity, composition and response to temperature
- Precipitation
 - Means and extremes
 - Averages 750-1250 mm (30-50 in) per year, most of which falls as snow (Fites). Millar et al. (2004) found a high degree of temperature and precipitation synchrony with six weather stations located in upper elevation forests of the central Sierra Nevada.
 - Central Sierra Nevada
 - Precipitation has increased by 15-48% since 1929-34 (Dolanc, 2012)
 - From 1910-20, precipitation averaged 41.7 cm; in 1990-2000, average precipitation increased to 63.2 cm in upper elevation forests of the central Sierra Nevada (Millar et al., 2004).
 - System's sensitivity, composition and response to precipitation
 - Water supply may be an important factor dictating the response of high elevation forests (Fites). The establishment of Jeffrey pine, sugar pine, and red fir are significantly associated with El Nino events which cause



wetter and warmer average conditions and a deep snowpack in the winter (North, 2005).

2. Sensitivity of component species

- Dominant species
 - The limber pine appears to be more drought hardy and may have higher genetic diversity, allowing for adaptation to drought conditions relative to the whitebark pine. The whitebark pine does not appear to have the adaptive genetic diversity for drought and warmth. (Millar, 2010).
 - Maximum growth occurs with high winter precipitation and warm summers for the foxtail pine, lodgepole pine, and western white pine but there is substantial species to species variation (Fites)
 - From the early 1930s to the 1990s, young mountain hemlock increased their density and basal area but large western white pine populations decreased. whitebark pine density increased and had more young trees. Similarly, lodgepole pine appears to be responding favorably to warming trends and increased precipitation. Lodgepole pine, western white pine and mountain hemlock all show decreased mortality (Bouldin, 1999).
- Ecosystem engineers
- Keystone species

3. Sensitivity to changes in disturbance regimes

- Wildfire
 - Fire does not structure the alpine and sub-alpine ecosystems as much as it does systems at lower elevations. Historically, forest fires occur in the subalpine roughly every century. Fire frequency increases with earlier snowmelt and warmer temperatures. But, the area burned by fire and the fire severity is expected to increase with a changing climate in the alpine and sub-alpine. Models indicate that there may be a 125% increase in small wildfires that cannot be readily suppressed and turn into large wildfires. This could cause a potential increase in the area burned at high elevation by 41% (Fites).
- Disease
 - Native fungal diseases include annosus root disease, armillaria root disease and black-stain root disease. Annosus root disease may be spreading more easily to the more dense forests that have been created by fire suppression (Fites)
 - White Pine Blister rust was introduced from Asia. It attacks five-needled pine species but the sugar pine is particularly susceptible (Fites)
 - Dwarf mistletoe is thought to be currently limited by climate but, climate change may extend its range to higher elevations and further north as temperatures warm and the growing season lengthens.
- Flooding



- If more precipitation falls as rain, less as snow, or warmer temperatures cause an earlier snowmelt, flooding and/or water logged soils could become more common in the subalpine and alpine regions.
- Insects
 - Mountain Pine beetles
 - Two major mortality events in the whitebark pine and limber pine occurred in 1988-1992 and 2006-current. Events occurred in monotypic, closed-canopy, relatively young stands located on the eastern edge of the escarpment on north/northeast aspects with slopes >40% at elevations between 2740-2840 m. The ultimate cause of tree death was the mountain pine beetle (Fites). Infestation was enhanced by increasing minimum temperatures combined with drought. (Millar, 2010)
- Wind
 - Winds can be high and can limit plant growth by battering plants or through enhanced evapotranspiration. Many trees in the subalpine and alpine region can develop twisted or bent forms due to the high winds (Fites).
- Drought

4. Sensitivity to other types of climate and climate-driven changes

- Altered hydrology
 - High elevation systems spend much of the year covered in snow. Snow pack often exceeds 3 m. 70-90% of precipitation falls as snow from October-April. Snowmelt typically begins between May and June (Roche, 2012). Avalanches on steep, north-facing slopes can disturb vegetation (Fites). Over the past 50 years, spring snowpack in the Sierra Nevada has decreased by 70-120% although there is a high degree of spatial heterogeneity; snowpack in the southern portion of the Sierra Nevada has increased. The reduction in snowpack will likely be greater at lower elevations in northern Sierra than in the higher elevations in the southern Sierra. Annual snowpack in the Sierra Nevada could decrease by 20-90% due to future climate change (Safford, 2010). Further, warmer temperatures are causing the spring thaw to occur earlier in the year; in 2002 it occurred 5-30 days earlier than in 1948. Peak streamflow occurred 5-15 days earlier in 2002 relative to 1948; March flows were higher by 5-20% but June flows were mostly lower (Safford). A change in the timing of snowmelt could also cause high elevation soils to become waterlogged due to early melt in the growing season but, then soils could experience subsequent droughts during late summer (Fites).
- Altered fire regimes
 - Prior to European settlement in the region, fires in the southern Sierra Nevada subalpine are thought to have been more frequent relative to recent trends. However, it is unclear if this is a landscape wide trend or isolated to localized areas. The historical fires were often not severe enough to be stand replacing (Caprio, 2008). At elevations above 2500 m, the fire-return interval before the mid 1800s was greater than 50 years (Fites). Because fire is relatively rare at



higher elevations, the fire management strategy implemented in the early 1900s did not impact high altitude forests as much as it did its lower elevation counterparts. Since the late Holocene, forest fires at high elevations seem to be driven by the intensification of ENSO (Hallett, 2010)

- Evapotranspiration and soil moisture
 - Higher summer temperatures could increase evapotranspiration rates and decrease the amount of moisture stored in the soils. This could cause a shorter growing season due to lack of moisture.
 - If winds increase, evapotranspiration rates will also increase.
- Extreme precipitation and temperature
 - In general, most models predict that the frequency of extreme precipitation will increase. Estimates range from an increase of 11-40% by 2049 and 18-55% by 2099 (Das, 2011).
- Water temperature
 - Along the entire western slope of the Sierra Nevada at elevations around 3500m, climate warming is projected to warm stream temperatures approximately 1.2°C for every 2°C rise in average annual air temperature. At higher elevations, stream temperature is expected to have a non-linear relationship with atmospheric warming meaning that temperatures rise progressively larger amounts with warming. At higher elevations, streams are not expected to experience temperatures above 21°C until air temperatures have increased by 4°C. High elevation streams in the central to north portion of the Sierra Nevada appear to be more susceptible to increases in the average annual number of weeks stream temperatures exceed 21°C; the watersheds of the southern Sierra Nevada appear to be less vulnerable to changes in thermal regimes (Null, 2012).
- Storm frequency and intensity
 - Warmer temperatures may cause a greater number of extreme convective storms, including enhanced occurrence of lightning strikes (Hallett, 2010).

5. Sensitivity to impacts of other non-climate-related threats

- Residential and commercial development
 - There is little commercial or residential developments at these high elevations.
- Agriculture and aquaculture
 - Subalpine meadows experienced extensive degradation in the late 1800s due to cattle grazing. The livestock trampling broke down the soil, allowing streams and erosion to occur, which lowered the water table. Meadow vegetation will only return where the water table is restored to its natural height or, near the surface (Odion). In a study of 24 meadows that were open to cattle grazing, located on the western slope of the central Sierra Nevada at elevations of 2,200-2,700 m, cattle use was negatively correlated to meadow wetness (Roche, 2012)
- Energy production and mining
- Transportation and service corridors
- Biological resource use
- Altered interspecific interactions



- Human intrusions and disturbance
- Natural system modification
- Invasive and other problem species
 - The high elevation forests have had relatively few invasive or exotic species establish in the ecosystem. This could be due to the limited activity by humans in the area, the harsh climate, or relatively intact canopies (Zouhar, 2008).
- Pollution and poisons
 - Ozone and nitrogen levels are relatively low at high elevations and do not appear to harm the ecosystem (Fenn, 2003).
- Geological events

6. Other Sensitivities

- Management

Adaptive Capacity

1. Habitat Extent and Characteristics

- Geographic extent in California

2. Landscape Permeability

- Barriers to dispersal or fragmentation
 - Many species in the subalpine and alpine area have limited room to vertically migrate because they are already located at the higher elevations of the Sierra Nevada. The area available to occupy decreases with elevation. Because of this, models have predicted a 70-95% loss in alpine/subalpine forest relative to 1961-1990 stands (Hayhoe, 2004). However, narrow and deep canyons may provide cool, wet refuge habitats. Some paleo-studies have suggested that the ecosystem moved downhill during long droughts.
 - Limber pine is recruiting below its lower forest border (Millar, presentation)

3. Habitat Diversity and Community Structure

- Diversity of component species
 - Whitebark pine (*Pinus albicaulis*) in subalpine zones of eastern California experienced significant mortality from 2007 to 2010. Dying stands were dense (mean basal area 47.5 m²/ha), young (mean 176 years), and even-age; mean stand mortality was 70%. Stands were at low elevations (mean 2993 m), on northerly aspects, and experienced warmer, drier climates relative to the regional species distribution (Miller et al., 2004).
 - Lodgepole pine, western white pine, and mountain hemlock have decreased mortality rates since the 1930s (Bouldin, 1999).



- Community Structure
 - In general, many species in the alpine and subalpine are experiencing enhanced growth. Tree growth over the 20th century has increased, with spiked increases from 1920-1945 and after 1980, corresponding to the Pacific Decadal Oscillation (PDO) and higher minimum temperatures (Millar, 2004). Since 1929-34, 6 of 8 tree species increased small tree densities at both the upper and lower boundaries of subalpine. Tree composition was the same (Dolanc 2012). 139 sites from 1929-34 were resampled in the Central Sierra Nevada at elevations of 2300-3400m. Tree stem density increased by 30.4% with a 63.3% increase in small trees but a 20% decrease in large trees. Warming temperatures plus steady to increasing precipitation have led to less stressful conditions for recruitment and survival of small trees, and are probably contributing to increased mortality of large trees. (Dolanc, 2012). Rates of annual tree growth in some species is a function of summer temperature and winter precipitation (Fites)
 - Trees are colonizing historically subalpine meadows (Millar, 2004). Trees are also increasingly occupying formerly persistent snowfields since the 1900s with pulses correlated to PDO and minimum temperature (Millar, 2004).
 - During milder conditions, tree growth tends to be more upright (flags and skirts); harsher conditions, tree growth tends to be in the krummholz form. Trees in the subalpine and alpine are increasingly being found as flags and skirts, more upright but, the growth response is reversible. (Millar, presentation).
 - High elevation ecosystems experience harsh conditions and suitable growing conditions only exist for an average of 6-9 weeks a year (Fites). Most plants are very slow growing but long lived. Plants in this zone can remain reproductively active for decades to centuries. There is a strong decline in the forest turnover with increasing elevation. Turnover rates of trees taller than breast height (1.4 m) near the treeline can be as low as 0.5% per year at higher elevation; seedling turnover can be 2.5% per year which is much lower when compared with the 2% and 10% relative turnover rates seen at lower elevations (Fites)



Exposure

Models of climate change in the Sierra Nevada predict uphill migration (Van de Ven et al. 2007) and restricted distribution of alpine/subalpine plant communities (Van de Ven et al. 2007, Lenihan et al. 2006). In the three scenarios modeled by Lenihan et al. (2006) to the end of the century, alpine/subalpine forest experienced significant declines in extent, particularly under the warmest conditions. Scenarios with longer and warmer growing seasons resulted in replacement of alpine/subalpine forest at high elevations with other vegetation types. Van de Ven et al. (2007) modeled predicted distributions of 14 alpine and subalpine species in the (arid) White and Inyo Mountains to an increased temperature of 6°C, in 1° increments. All species are predicted to shift upslope and decrease their ranges due to this shift. Some shifted from south to north facing slopes, and previously continuous habitat became fragmented. At an increase of 3°C (5.4° F), 2 species became extinct, and the new ranges of the remaining species areas were 68% or less of current areas. At an increase of 6°C (10.8° F), 10 out of 14 species disappeared from the study area, and the remaining 4 shrank to 1% of their current ranges.

An empirical study by Diaz et al. (2007) found that rising temperatures between 1987-2007 resulted in a 73% reduction in coverage of “Koppen” alpine tundra in the western United States, as temperatures exceeded the threshold (10°C or 18° F) for this classification. Remaining alpine tundra averages between ~9-10°C (16.2 - 18° F) in the warmest month, suggesting that classified alpine tundra will no longer be present with continued warming (Diaz et al. 2007).

The comparative stasis of foxtail pine (*Pinus balfouriana*) in Sequoia National Park during the last 100-200 years indicates that there are steep gradients of vulnerability to climate change at treeline in the Sierra Nevada (Lloyd 1997).

Because climate change is not a smooth, linear shift to warmer temperatures, these fine and mesoscale predictions do not account for “ecological inertia”, which may result in new, transitory associations. Species with wind-dispersed seeds and with lifespans on the order of decades (see: Mozingo 1987) may rapidly establish new, higher-elevation sites (Van de Ven et al. 2007). Weedy annuals may respond most rapidly, possibly at the expense of existing species. Plants that infrequently reproduce sexually, such as forbs, (see: Spira 1991) may have difficulty responding. The amount of time required for species’ distributions to equilibrate into the ranges predicted in the White and Inyo Mountains varies by orders of magnitude by species, from possibly thousands of years to a few years (Van de Ven et al. 2007).

The paleoecological record provides evidence that forests have responded to past climatic changes in complex ways (Millar et al. 2004, 2006, Lloyd and Graumlich 1997, Lloyd 1997, Taylor 1995) and Millar et al. (2006) suggest that such trends may ensue under future warming. Rather than simple upward or downward movements of the treeline boundary seen in general projections, responses to past climate variation often occur in unanticipated and nonlinear patterns, such as abrupt changes and reversals (Millar et al. 2004, 2006) and involve complex changes in distribution and forest structure (Lloyd and Graumlich 1997). Millar et al. (2006) found that, despite differences in CO₂ levels, Medieval climatic conditions were similar to those projected for 2070-2099 in Whitewing Mountain and San Joaquin, Mono County, but produced



a significant increase in subalpine forest extent and diversity, in contrast to the estimated 75-90% reduction of subalpine forest projected based on vegetation-climate projections.

A warming-induced rise in treeline elevation is likely to involve landscape-scale increases in biomass, productivity, and carbon pools as a result of increases in forested area and density (Lloyd & Graumlich 1997). However, the paleoecological record indicates that future warming is unlikely to cause an expansion of subalpine forests if it is accompanied by a reduction in water supply (Lloyd & Graumlich 1997).

Moreover, data on alpine microclimate traits suggest that models predicting upslope movements of species under increasing temperatures may not be entirely realistic, and that sufficient microclimate heterogeneity may slow such migration. Graham et al. (2012) built upon work by Scherrer and Korner (2010, 2011) which revealed large and persistent microhabitat temperature variations over mesoscale alpine landscape, mimicking temperature gradients of several hundred meters of elevation, suggesting that alpine plants may find appropriate thermal niches for establishment and survival without elevational shifts. Graham et al. (2012) found that alpine fellfield topographic variability in the White Mountains creates 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. However, understanding of the relative significance 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).

Although warming at high elevations is commonly assumed to exert primary effect by causing altitudinal shifts in treeline, complex changes in spatial distribution, productivity, and type conversions below treeline may be more important, at least in the early decades of the 21st century (Millar et al. 2004).

Bristlecone pine

A strong positive relationship exists between temperature and treeline growth (ring width) of bristlecone pine (*Pinus longaeva*). Although Salzer et al. (2009) found no clear decadal-scale relationship between precipitation and growth, weaker positive associations at sites in Sheep Mountain, California, Mt Washington, Nevada, and Pearl Creek, Nevada may indicate precipitation contributed to growth (Salzer et al. 2009).

As temperatures increase, bristlecone pine (*P. longaeva*) migrates to higher elevations in the White and Inyo mountains, where its habitat availability is limited by its aversion to granitic substrates. With an increase in temperature of 5°C (9° F), carbonate substrates at high enough elevations may not be available (Van de Ven et al. 2007).

Van de Ven et al. (2007) assert that despite temperature increases, individual bristlecone pine may survive hundreds of years at low-elevations due to slow dieback and local refugia, while species like *Pinus monophylla* and *Juniperus osteosperma* rapidly migrate upslope, resulting in



rare, transitory forest associations. The combination of bristlecone–pinyon–juniper forest is currently very rare in the White Mountains but could become more commonplace as temperatures increase (Van de Ven et al. 2007).

Foxtail Pine

A study by Lloyd (1997) found that historic records of foxtail pines (*Pinus balfouriana*) in Sequoia National Park exhibited a lack of population sensitivity to paleoclimate summer temperatures and winter precipitation in treeline forests during the last 1000 years. Foxtail pine recruitment displayed less variability than mortality, and while rates of recruitment and changes in treeline stand density were inversely correlated with summer temperature, mortality rates were uncorrelated with precipitation and temperature. The inverse correlation of temperature and recruitment may indicate an important role for water balance in regulating population growth (Lloyd 1997).

Life history characteristics which reduce moisture and nutrient requirement (Bunn et al. 2005) and moderate densities of adult trees, which are able to moderate their microclimate, may provide resistance to climate change, while trees in marginal locations do not experience the full protective influence of this buffering (Lloyd 1997). Foxtail pines in drier regions of the cold and dry eastern crest of Sequoia National Park may lose the ability to grow in warm temperatures if insufficient water leads to drought stress (Bunn et al. 2005)

The downslope expansion of foxtail pine is correlated with the distribution of shade-tolerant conifers, which are in turn correlated with habitat heterogeneity (i.e., boulder cover and ultramafic substrates). This implies that although climate change may be the driving force behind expansions, within the Klamath Mountains, downslope expansion can be facilitated by habitat heterogeneity (Eckert and Eckert 2007).

Whitebark Pine

Millar et al. 2004 found that in the Sierra Nevada, response of treeline whitebark pine (*Pinus albicaulis*) annual branch growth rates to warming and climate variability throughout the 20th century were directional and ongoing, from low to high. During this period, populations of whitebark pine and lodgepole pine (*Pinus contorta*) in southeastern Sierra Nevada had increasing growth trends, regardless of age or competitive relations of trees. Krummholz whitebark pine (*P. albicaulis*) thickets at the upper treeline in the Sierra Nevada, displayed abundant vertical branches in the latter part of the century, compared to the compact, flat-topped crowns at the start of the century, producing a mixed krummholz-upright tree structure to this zone (Millar et al. 2004).

Western White Pine

Millar et al. 2004 found that in the Sierra Nevada, response of colonization rate of western white pine (*Pinus monticola*) into formerly persistent snowfields below treeline to warming and climate variability throughout the 20th century were directional and ongoing, from minimal to significant establishment.



OTHER

Mountain Hemlock

The temperature driven change in the mountain hemlock (*Tsuga mertensiana*) forest in the last 150 years suggests that predicted warming (Houghton et al., 1992) will have a significant effect on these forests in Lassen Volcanic Park and elsewhere in the Pacific Northwest. During that period, near treeline mountain hemlock forests have increased in density, warming triggered population expansion, and initial recruitment peaked during a warm mesic period. Recruitment response is spatially variable, however, because high precipitation (i.e., high snowpack) retards recruitment on mesic flats with late lying snow and promotes it on xeric sites. Despite cooling since the 1940s, mountain hemlock populations have continued to expand, suggesting that tree patches provide microclimatic amelioration and cause recruitment despite unfavorable climatic conditions (Taylor 1995).

Subalpine meadow

By the end of the 20th century, subalpine meadows in the Sierra Nevada experienced episodic invasion of pine, changing from meadows previously dominated by grasses, sedges and forbs, and displaying abrupt borders with surrounding forest, to having less distinct borders, with pines scattered throughout the meadow (Millar et al. 2004).



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