CalVeg types included: **RFR**- Red fir (*Abies magnifica*), white fir (*Abies concolor*), lodgepole pine (*Pinus contorta*)

Sensitivity Assessment

1. Direct sensitivities

- Temperature
  - Means and extremes
    - Historic
      - In general, the climate of the red fir forest can be classified as cool. At Huntington Lake (elev. 2830 m), nearby the Sequoia National Monument, mean annual temperature has risen by 1.8 ^{o}F over roughly the past century. This trend is most strongly driven by an increase in nighttime minimum temperatures of 4 ^{o}F since 1915; indeed, months that experience below freezing have dropped from 6-7 months a year to closer to five. Similar trends are seen at nearby weather stations (Safford, 2010).
    - Future
      - Over the next century, average temperatures in California are expected to increase by 2-4 ^{o}F in winter and 4-8 ^{o}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
    - Warmer temperatures may partially explain recent die offs of the red fir at lower elevation stands in the Tahoe National Forest. Low elevation red fir forests may be converted to vegetation zones like oak woodland or Douglas fir (Gonzalez, 2010).
- Precipitation
  - Means and extremes
    - Historic
      - Almost all precipitation occurs between October and March, 80% of that in the form of snow. Total precipitation ranges from 30 to 60 inches. At Huntington Lake (elev. 2830 m), nearby the Sequoia National Monument, average annual precipitation has increased over the past century from 25.6 inches per year in 1915 to 45.6 inches per year in 2009. However, precipitation patterns can be very heterogeneous both inter-annually and across landscapes and other, nearby weather stations do not show statistically significant trends in time or in space (Safford, 2010).
    - Future
  - System's sensitivity, composition and response to precipitation
    - The best growth of the red fir appears to occur in areas that receive 30-49 inches of precipitation. Red fir recruitment is associated with El Nino

events and may be due to enhanced winter snowpack and soil moisture levels (North, 2005).

- The red fir/white fir ecotone has been shown to correspond with snowpack. Red fir dominates in areas that had a high degree of annual snowpack on April 1; white fir is more common below this. Mean freezing level during storms from December to March centers on the ecotone. (Barbour, 1991). Lodgepole pine occupies wet sites in red fir forests. Dry sites are occupied by the sugar pine, mountain hemlock and incense cedar.

2. Sensitivity of component species

- Dominant species
  - Red fir forests have increased their density of young trees by about 40% from 1935 to 1992; over the same timeframe however, densities of large trees decreased by about 50%. Mortality rates in the red fir increased the most in the smaller size classes. Red fir is considered to be a climax species. Jeffrey pine and western white pine populations have decreased and are being replaced by more shade tolerant species like mountain hemlock (Bouldin, 1999). White fir may be better suited to adapt to the impacts of climate change relative to the red fir. (Laacke, 1996)
- Ecosystem engineers
  - Pocket gophers (*Thomomys* sp.) burrowing behavior has been shown to reduce the establishment of red firs in otherwise open patches of land. This can cause a patchwork effect in forests, increasing heterogeneity (Laurent, 1994).
- Keystone species

3. Sensitivity to changes in disturbance regimes

- Wildfire
  - Fire effects on red fir forests are poorly understood (Caprio, 1999). Fires in the red fir forest are dominated by low to moderate intensity fires, causing a patchwork of ages in trees. Relative to ponderosa pine or sugar pine, red fir is less fire tolerant. Intense fires result in high mortality for red firs. Thus, low intensity fires are thought to be enough of a disturbance to open up the canopy (Kane, 2013).
  - Lodgepole pine is a pioneer species, quickly establishing and early seral stage forest after a fire. Red fir seedling establishment occurs usually 3-4 years post fire.
- Disease
  - Dwarf mistletoe is a common ailment in the red fire forest and infests roughly 40% of the stands in California. It can make the tree more susceptible to insect infestations. Similarly, trees infected by dwarf mistletoe maybe be more

    - vulnerable to drought. In lodgepole pine, dwarf mistletoe currently occurs in the lower elevation forest but not at the upper elevation limits of the pine itself.
    - Fir broom rust is common in the central and southern Sierra Nevada but is generally not lethal.
    - Annosus root rot becomes more of a problem in more dense stands.
- Flooding
- Insects
    - A 2006 model estimated that 1.4 million acres of forest were susceptible to high levels of mortality due to insects and disease, where 'susceptible' is defined as the expectation that 25% or more of the standing tree volume would die over the next 15 years. Red and white fir are attacked by the fir engraver beetle and the lodgepole and ponderosa pine are attacked by the mountain pine beetle (Living Assessment, 2013). In contrast, a 1996 (Laacke) report claimed that insect infestations are relatively rare in the red fir forest.
- Wind
- Drought
    - Red fir appears to be more sensitive to drought than white fir but, red fir also exhibits poor growth in water logged soils.
    - Drought may be an important, negative controlling agent of red fir regeneration after a fire.

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

- Altered hydrology
    - 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. At higher elevations near Huntington Lake (elev. 2830 m), snowpack has not diminished over the past century. In fact, snowfall at this weather station showed an increase from 200 inches to 150 inches over the time period of 1915 to 1973 (Safford, 2010). In general, 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).
    - In the future, runoff in the winter and early spring may be higher due to earlier and quicker melting of the snowpack due to warmer temperatures. Temperature is thought to be more of a controller on peak runoff than is precipitation. However, under the wettest climate scenario, by 2100 the volume of flow in some Sierra Nevada rivers could double during the highest flow days (Miller, 2003).
- Altered fire regimes
    - Historically, fire frequency in the red fir forest occurred >50 years but fire suppression policy instated in the early 1900s has reduced the fire frequency in these forests (Miller, 2009). A fire exclusion policy was instated in the beginning

of the early 20th century. Reduced fire frequency increased forest density and shifted the forest composition to less fire tolerant species and more shade tolerant species.

- Evapotranspiration and soil moisture
  - Soils in red fir forests have very slow nutrient recycling and thus, trees can be nutrient stressed.
- 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 ranging from 1500-2500 m, climate warming is projected to warm stream temperatures approximately 1.6 oC for every 2 oC rise in average annual air temperature. Stream temperatures warmed the most during spring. Between wet and dry years, stream temperatures reach similar maxima but, warm water conditions (greater than 18 oC) persisted for 1-2 months during wet years and increased to 3-4 months during dry years. 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 oC; 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. Non-climate Related Threats

- Residential and commercial development
- Agriculture and aquaculture
- Energy production and mining
  - Red fir forests were not burned nor cleared for mining.
- Transportation and service corridors
- Biological resource use
  - Red fir forests were not logged historically because they were too far from timber markets. However, recently their harvest has become more common because their wood is very valuable.
- Altered interspecific interactions
- Human intrusions and disturbance
  - Red fir forests are considered to be one of the least altered from its “natural state” by anthropogenic forces. This is due to its relatively high elevation and rough terrain.
- Natural system modification
- Invasive and other problem species

    - At higher elevations, there are few invasive species.
- Pollution and poisons
- Geological events

6. Other Sensitivities

- Management

Adaptive Capacity

1. Extent and Characteristics

- Geographic extent in California
    - Red fir is limited to high elevations and ranges from the central Cascade Mountains to southern Sierra Nevada. It typically occurs at elevations above 1800 m. Red fir can also be found at lower elevations in canyons and cool riparian zones.
    - During the Holocene period, the Giant Sequoia could be found upslope and likely grew above its present elevational range. In contrast, the lodgepole pine was a key forest component below its current range and was found at lower elevations (Anderson).
    - Sediment cores tell a similar story of shifting species compositions at elevations now occupied by red fir. During the Pleistocene, these areas were once occupied by sagebrush. Then a rapid shift (500 year) transition occurred about 12,500 yr BP during which pine trees began to colonize. This shift is likely a response to the shift from glacial climates. Since the Holocene, the forest has slowly evolved from a pine forest to the red fir forest seen today (West, 2003).

2. Landscape Permeability

- Barriers to dispersal or fragmentation

3. System Diversity

- Diversity of component species
    - The California red fir may be able to hybridize with a more northern species, the noble fir. The two species can be manually cross pollinated as long as red fir is the female parent. (Zavarin, 1978).
    - The red fir's growth does not correlate well with climate. This may be due to the fact that red fir commonly grows in a buffered, riparian zone that reduces its sensitivity to annual climate fluctuations (Hurteau, 2007). Indeed, it has been shown that the best predictor of tree growth is the red fir is the tree's diameter at the beginning of the growth period which explains 58% of the growth patterns seen in the following 10 years. The second most important predictor variable

was the crown ratio, of the percent of tree stems that have live foliage on it; this may be an estimate of tree vigor (Dolph, 1992). In contrast, White fir growth most closely follows trends in climate (Hurteau, 2007).
    - In the Pacific Northwest, Lodgepole pine has been found to grow best at sites with significant spring frost, summer temperatures averaging <15 ^{o}C and soils that fully recharged from snowmelt. In the Pacific Northwest, climate change is thought to initially expand the habitat for the lodgepole pine but, by 2100, the expanded habitat will be better suited for other tree species and the lodgepole pine could be absent from much of its current range (Coop, 2011).
- Community structure
    - Red fir forests may be able to extend its range to higher elevations as temperatures warm and the growing season at elevation lengthens.
        - "Pollen of white and red fir (*Abies concolor* and *A. magnifica*) and mountain hemlock suggests that during the early Holocene these species were only minor components of the Sierra Nevada forests. However, by approximately 6,000 years ago, each of these species increased in abundance, perhaps largely in response to changing climate and higher soil moisture levels (Anderson and Smith1994). Because each of the tree species that increased during the late Holocene depends upon readily available soil moisture during the summer growing season, it has been suggested elsewhere (Anderson 1990) that either a reduction in the length of the summer dry season, an increase in precipitation during the winter months (as snow, lasting longer into the spring), a reduction in temperature causing reduced evaporation, or some combination of these processes would have favored the above-mentioned conifers." (Anderson)

Exposure

A predominant effect of climate change in the Sierra Nevada regions will likely result from changes in vegetation communities, including loss of conifer dominated vegetation, such as red fir/ lodgepole pine, especially at higher elevations (Gardali et al. 2011). Based on climate scenarios, lodgepole pine distributions in California are predicted to increase slightly to 2020, then decrease significantly by the end of the century (Miller et al. 2003). The loss of red fir / lodgepole communities in the Sierra Nevada may be accelerated by changes in the severity and frequency of fire (Gardali et al. 2011). In contrast, Bartlein et al. (1997) characterize lodgepole pine as a fire-tolerant species, suggesting that more frequent fires may create opportunities for it to expand (in Yellowstone National Park in Montana) into areas where future climate supports appropriate fire regimes.

The change in modeled water deficit from present climate to future climate scenarios for Yosemite National Park is much greater than the change from the Little Ice Age to present. The increase in temperature projected decreased snowpack and increased summer potential evapotranspiration, resulting in modeled increases in deficit of 23% across all plots. Models showed a significant increase in deficit for all tree species, with deficit exceeding 25% for plots in Yosemite National Park were occupied by California red fir, lodgepole pine, western juniper, whitebark pine, western white pine, giant sequoia and mountain hemlock (Lutz et al. 2010). The forecasted increase in deficit may be partially offset by increases in actual evapotranspiration in spring and autumn. Individual trees that established c. 1700 may be at risk of deficit related mortality if they are located near the North American range limit for the species. Some plots in Yosemite National Park occupied by white fir and red fir may fall into this category (Lutz et al. 2010).

Lutz et al. (2009) found that between the 1930s and 1990s in Yosemite National Park, both lodgepole pine and white fir had increases in mortality of large-diameter trees throughout their elevational ranges. In contrast, Millar et al. (2004) found that lodgepole pine in the southeastern Sierra Nevada exhibited trends of increasing growth throughout the 20th century, supporting an analysis by Safford et al. (2012) indicating that subalpine lodgepole pine experienced decreases in mortality in the Sierra Nevada between 1935 and 1992.

Red fir displayed little or no change in large-diameter tree densities in Yosemite National Park during the 1930 to 1990 period (Lutz et al. 2009). Hurteau et al. (2007) suggest that the poor climate-growth relationship of red fir in the Teakettle Experimental Forest in southern Sierra Nevada could be a result of buffering by microclimate at locations within the riparian zone. Bouldin (1999) found that the greatest increases in mortality patterns of red fir in the Sierra Nevada from 1935 and 1992 were for smaller size classes (Safford et al. 2012).

For red fir open growing conditions did not improve climate model fit of radial growth patterns. As forest conditions become increasingly dense from a century of fire suppression, it may become more difficult to identify species and individuals that can provide the best annual growth to climate response. Hurteau et al. (2007) suggest that a tree's annual growth response to climate can be influenced by its species characteristics and localized differences in stand density.

Davis and Shaw (2001) suggest that to expect trees to track shifting climate assumes that tree taxa more readily disperse seed and establish in new regions within current tolerance ranges than evolving a new range of climatic tolerances. Instead, they suggest that future responses may be explained in part by intraspecific genotypic differentiation, which is likely to also affect future biotic response to climate change (Davis and Shaw 2001).

Pests

Increases in temperature regimes and shift in precipitation events may increase the susceptibility of lodgepole pine to pests. The mountain pine bark beetle (*Dendroctonus ponderosae*) is a recognized threat to pine species, primarily lodgepole pine, in western North America (Coops et al. 2012, Murdock et al. 2013). Studies in western Canada indicate that increased size and severity of mountain pine beetle outbreaks have been attributed to the reduced severity of winter temperatures, and to the increased abundance of its principal host, lodgepole pine (Coops et al. 2012, Murdock et al. 2013).

Sierra red fox

No information

Primary sources

Anderson, S.A., S.J. Smith. 1994. Paleoclimatic interpretations of meadow sediment and pollen stratigraphies from California. *Geology*. 22: 723-726.

Anderson, S.A. 2002. Responses of Sierra Nevada Vegetation and Fire Regimes to Past Climate Changes.

Barbour, M.G., N.H. Berg, T.G.F. Kittel, M.E. Kunz. 1991. Snowpack and the distribution of major ecotone in the Sierra Nevada Mountains of California. *Journal of Biogeography*. 18: 141-149.

Bartlein, P. J., Whitlock, C. & Shafer, S. L. (1997.) Future climate in the Yellowstone National Park region and its potential impact on vegetation. Conservation Biology, 11(3), 782 – 792.

Bouldin, J. 1999. Twentieth century changes in forests of the Sierra Nevada, California. PhD. Dissertation. University of California, Davis.

Caprio, A. 1999. 1999 Annual fire report on research, montoring and inventory: red fir plots.

Coop, N.C., R.H. Waring. 2011. A process based approach to estimate lodgepole pine distribution in the Pacific Northwest under climate change. *Climatic Change*. 105: 313-328.

Coops, N. C., Wulder, M. A. & Waring, R. H. (2012). Modeling lodgepole pine and jack pine vulnerability to mountain pine beetle expansion into the western Canadian boreal forest. Forest Ecology and Management, 274, 161 – 171.

Davis, M. B. & Shaw, R. G. (2001). Range shifts and adaptive responses to Quaternary climate change. Science, 292, 673 – 679.

Dolph, K.L. 1992. A diameter increment model for red fir in California and southern Oregon. Res. Paper PSW-RP-210. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 6 p.

Gonzalez, P., J.J. Battles, and K.M. Waring. 2009. Climate change and the detection of possible elevation shifts of forest species in the Sierra Nevada, California. Ecological Society of America Annual Meeting Abstracts 94: OOS 30-8.

Heineman, J. L., Sachs, D. L., Mather, W. J. & Simard, S. W. (2010). Investigating the influence of climate, site, location, and treatment factors on damage to young lodgepole pine in southern British Columbia. Canadian Journal of Forest Research, 40, 1109 – 1127.

Hurteau, M., Zald, H. & North, M. (2007). Species-specific response to climate reconstruction in upper-elevation mixed-conifer forests of the western Sierra Nevada, California. Canadian Journal of Forest Research, 37, 1681 – 1691.

Kane, V.R., J.A. Lutz, S.L. Roberts, D.F. Smith, R.J. McGaughey, N.A. Povak, M.L. Brooks. 2013. Landscape scale effects of fire severity on mixed conifer and red fir forest structure in Yosemite National Park. *Forest Ecology and Management*. 287: 17-31.

Laacke, R.J., J.C. Tappeiner. 1996. Red fir ecology and management. Avail at http://pubs.usgs.gov/dds/dds-43/VOL_III/VIII_C10.PDF. Accessed on Feb. 28, 2013.

Laurent, T.E., R.C. Graham, K.R. Tice. 1994. Soils of the red fir forest barrens mosaic, Siskiyou Mountains Crest, California. *Soil Science Society of America Journal*.

Living Assessment. 2013. Chapter 2 Bio-region: Sierra Nevada bio-region. Avail at http://livingassessment.wikispaces.com/Chapter+2+Bio-region. Accessed on Feb.28 2013.

Lutz, J. A., van Wagtendonk, J. W., & Franklin, J. F. (2009). Twentieth-century decline of large-diameter trees in Yosemite National Park, California, USA. Forest Ecology and Management, 257, 2296-2307.

Millar, C. I., Westfall, R. D., Delany, D. L., King, J. C. & Graumlich, L. J. (2004). Response of subalpine conifers in the Sierra Nevada, California, U. S. A., to 20th-century warming and decadal climate variability. Arctic, Antarctic, and Alpine Research, 36(2), 181 – 200.

Miller, N. L., Bashford, K. E., & Strem, E. (2003). Potential Impacts of Climate Change on California Hydrology. Journal of the American Water Resources Association, 1093-474x, 39(4), 771-784.

North, M., M. Hurteau, R. Fiegener, M. Barbour. 2005. Influence of fire and El Nino on tree recruitment variet by species in Sierran Mixed Conifer. *Forest Science*. 51(3).

Null, S.E., J.H. Viers, M.L. Deas, S.K. Tanaka, J.F. Mount. 2012. Stream temperature sensitivity to climate warming in California's Sierra Nevada: impacts to coldwater habitat. *Climate Change*.

Safford, H. 2010. A summary of current trends and probably future trends in climate and climate-drive processes in the Giant Sequoia National Momument and the neighboring Sierra Nevada.

Safford, H. D., North, M. & Meyer, M. D. (2012). Climate change and the relevance of historical forest conditions. In M. North, Malcolm, ed. Managing Sierra Nevada forests. General Technical Report PSW-GTR-237. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.

West, J.G. 2003. A late Pleistocene-Holocene pollen record of vegetation change from Little Willow Lake, Lassen Volcanic National Park, California. 2003 PACLIM Conference Proceedings. Avail at http://tenaya.ucsd.edu/~dettinge/PACLIM/09_West_03_final.pdf.

Zavarin, E., W.B. Critchfield, K. Snajberk. 1978. Geographic differentiation of monoterpenes from *Abies procera* and *Abies magnifica*. *Biochemical Systematics and Ecology*. 6: 267-278.

Secondary sources

Bouldin, J. 1999. Twentieth-century changes in forests of the Sierra Nevada, California. Davis, CA: University of California, Davis. 222 p. Ph.D. dissertation.