Focal Resource: RED FIR

CWHR Types: RFR[1]: Red fir (*Abies magnifica*), white fir (*Abies concolor*), lodgepole pine (*Pinus contorta*)

General Overview of Process

EcoAdapt, in collaboration with the U.S. Forest Service and California Landscape Conservation Cooperative (CA LCC), convened a 2.5-day workshop entitled *A Vulnerability Assessment Workshop for Focal Resources of the Sierra Nevada* on March 5-7, 2013 in Sacramento, California. Over 30 participants representing federal and state agencies, non-governmental organizations, universities, and others participated in the workshop[2]. The following document represents the vulnerability assessment results for the **RED FIR ECOSYSTEM**, which is comprised of evaluations and comments from a participant breakout group during this workshop, peer-review comments following the workshop from at least one additional expert in the subject area, and relevant references from the literature. The aim of this synthesis is to expand understanding of resource vulnerability to changing climate conditions, and to provide a basis for developing appropriate adaptation responses. The resulting document is an initial evaluation of vulnerability based on existing information and expert input. Users are encouraged to refer to the Template for Assessing Climate Change Impacts and Management Options (TACCIMO, http://www.taccimo.sgcp.ncsu.edu/) website for the most current peer-reviewed literature on a particular resource. This synthesis is a living document that can be revised and expanded upon as new information becomes available.

Geographic Scope

The project centers on the Sierra Nevada region of California, from foothills to crests, encompassing ten national forests and two national parks. Three geographic sub-regions were identified: north, central, and south. The north sub-region includes Modoc, Lassen, and Plumas National Forests; the central sub-region includes Tahoe, Eldorado, and Stanislaus National Forests, the Lake Tahoe Basin Management Unit, and Yosemite National Park; and the south sub-region includes Humboldt-Toiyabe, Sierra, Sequoia, and Inyo National Forests, and Kings Canyon/Sequoia National Park.

Key Definitions

Vulnerability: Susceptibility of a resource to the adverse effects of climate change; a function of its sensitivity to climate and non-climate stressors, its exposure to those stressors, and its ability to cope with impacts with minimal disruption[3].

Sensitivity: A measure of whether and how a species or system is likely to be affected by a given change in climate or factors driven by climate.

Adaptive Capacity: The degree to which a species or system can change or respond to address climate impacts.

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[1] From California Wildlife Habitat Relationship (CWHR) habitat classification scheme see: http://www.dfg.ca.gov/biogeodata/cwhr/wildlife_habitats.asp.

[2] For a list of participant agencies, organizations, and universities please refer to the final report *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada* available online at: http://ecoadapt.org/programs/adaptation-consultations/calcc.

[3] Glick, P., B.A. Stein, and N.A. Edelson, editors. 2011. Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment. National Wildlife Federation, Washington, D.C.

Exposure: The magnitude of the change in climate or climate driven factors that the species or system will likely experience.

Methodology

The vulnerability assessment comprises three vulnerability components (i.e., sensitivity, adaptive capacity, and exposure), averaged rankings for those components, and confidence scores for those rankings (see tables below). The sensitivity, adaptive capacity, and exposure components each include multiple finer resolution elements that were addressed individually. For example, sensitivity elements include: direct sensitivity of the system to temperature and precipitation, sensitivity of component species within the system, ecosystem sensitivity to disturbance regimes (e.g., wind, drought, flooding), sensitivity to other climate and climate-driven changes (e.g., snowpack, altered hydrology, wildfire), and sensitivity to non-climate stressors (e.g., grazing, recreation, infrastructure). Adaptive capacity elements include: ecosystem extent, integrity, and fragmentation; ecosystem ability to resist or recover from stressors; landscape permeability; ecosystem diversity (e.g., physical, topographical, component species, functional groups); and ecosystem value and management potential. To assess exposure, participants were asked to identify the climate and climate-driven changes most relevant to consider for the ecosystem and to evaluate exposure to those changes for each of the three Sierra Nevada geographic sub-regions. Climate change projections were provided to participants to facilitate this evaluation[4]. For more information on each of these elements of sensitivity, adaptive capacity, and exposure, including how and why they were selected, please refer to the final methodology report *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada*[5].

During the workshop, participants assigned one of three rankings (High (>70%), Moderate, or Low (<30%)) to each finer resolution element and provided a corresponding confidence score (e.g., High, Moderate, or Low) to the ranking. These individual rankings and confidence scores were then averaged (mean) to generate rankings and confidence scores for each vulnerability component (i.e., sensitivity, adaptive capacity, exposure score) (see table below). Results presented in a range (e.g. from moderate to high) reflect variability assessed by participants. Additional information on ranking and overall scoring can be found in the final methodology report *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada*[5].

Recommended Citation

Hauptfeld, K., J.M. Kershner, and K.M. Feifel, eds. 2014. Sierra Nevada Ecosystem Vulnerability Assessment Technical Synthesis: Red Fir *in* Kershner, J.M., editor. 2014. *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada*. Version 1.0. EcoAdapt, Bainbridge Island, WA.

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

[4] Geos Institute. 2013. *Future Climate, Wildfire, Hydrology, and Vegetation Projections for the Sierra Nevada, California: A climate change synthesis report in support of the Vulnerability Assessment/Adaptation Strategy process.* Ashland, OR. http://ecoadapt.org/programs/adaptation-consultations/calcc.

[5] Kershner, J.M., editor. 2014. *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada.* Version 1.0. EcoAdapt, Bainbridge Island, WA. http://ecoadapt.org/programs/adaptation-consultations/calcc.

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Overview of Vulnerability Component Evaluations

SENSITIVITY

Sensitivity Factor	Sensitivity Evaluation	Confidence
Direct Sensitivities – Temperature	**3 High**	**2 Moderate**
Direct Sensitivities – Precipitation	**3 High**	**3 High**
Component Species	**3 High**	**2 Moderate**
Disturbance Regimes	**3 High**	**2 Moderate**
Climate-Driven Changes	**3 High**	**2 Moderate**
Non-Climatic Stressors – Current Impact	**1 Low**	**2 Moderate**
Non-Climatic Stressors – Influence Overall Sensitivity to Climate	**2 Moderate**	**2 Moderate**
Other Sensitivities	**2 Moderate**	**2 Moderate**

Overall Averaged Confidence (Sensitivity)[6]: Moderate

Overall Averaged Ranking (Sensitivity)[7]: Moderate – High

ADAPTIVE CAPACITY

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Extent and Integrity – Distribution	**2 Moderate**	**3 High**
Extent and Integrity – Fragmentation	**2 Moderate**	**2 Moderate**
Resistance and Recovery	**2 Moderate**	**2 Moderate**
Landscape Permeability	**1 Low**	**2 Moderate**
System Diversity – Physical/Topographical	**3 High**	**2 Moderate**
System Diversity – Component Species/Functional Groups	**1 Low**	**2 Moderate**
System Value	**3 High**	**3 High**
Specificity of Management Rules	**3 High**	**3 High**
Other Adaptive Capacities	**3 High**	**3 High**

Overall Averaged Confidence (Adaptive Capacity)[6]: Moderate-High

Overall Averaged Ranking (Adaptive Capacity)[7]: Moderate

EXPOSURE

Relevant Exposure Factor	Confidence
Temperature	**2.5 Moderate-High**
Precipitation	**1.5 Low-Moderate**
Shifts in vegetation type	**3 High**
Climatic water deficit	**1.5 Low-Moderate**
Wildfire	**2 Moderate**
Snowpack	**3 High**

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[6] 'Overall averaged confidence' is the mean of the entries provided in the confidence column for sensitivity, adaptive capacity, or exposure, respectively.

[7] 'Overall averaged ranking' is the mean of the perceived rank entries provided in the respective evaluation column.

Exposure Region	Exposure Evaluation (2010-2080)	Confidence
Northern Sierra Nevada	**2.5 Moderate – High**	**2 Moderate**
Central Sierra Nevada	**2.5 Moderate – High**	**2 Moderate**
Southern Sierra Nevada	**2 Moderate**	**2 Moderate**

Overall Averaged Confidence (Exposure)[6]: Moderate

Overall Averaged Ranking (Exposure)[7]: Moderate

Sensitivity

1. **Direct sensitivities to changes in temperature and precipitation.**
    a. Sensitivity to temperature (means & extremes): High
        i. Participant confidence: Moderate
    b. Sensitivity to precipitation (means & extremes): High
        i. Participant confidence: High

Additional comments: The red fir system may have limited ability to move upslope. Red fir prefers areas with 30-49 in (762-1245 mm) of precipitation per year. It is vulnerable to declining snowpack even if overall precipitation increases.

References:

Temperature: In general, the climate of the red fir forest can be classified as cool with summer temperatures rarely exceeding 29^{o}C and winter temperatures rarely below -29^{o}C (Laacke 1990). However, red fir commonly grows in a buffered, riparian zone that reduces its sensitivity to annual climate fluctuations (Hurteau et al. 2007). Hurteau et al. (2007) suggest that the poor climate-growth relationship of red fir in the Teakettle Experimental Forest in the southern Sierra Nevada could be a result of buffering by microclimate at locations within the riparian zone.

Climate change, as indicated by warmer mean annual temperatures, may partially explain reduction of the red fir at a high elevation stand between 1948-2004 in the Sierra Nevada (Gonzalez et al. 2009).

Precipitation: Red fir is confined to cool/moist areas, typically in the upper montane zone at elevations above 1829 m and 2286 m (6000 ft and 7500 ft) in the northern and southern Sierra Nevada respectively (Laacke 1990; Long et al. 2013).

Red fir recruitment is associated with El Niño events perhaps due to enhanced winter snowpack and soil moisture levels (Barbour et al. 1991; North et al. 2005).

Snowpack: The upper montane red fir forests of northern California experience the highest snowpack of any vegetation type in the state and are strongly correlated with long-term mean April 1 snow water equivalence (SWE) rather than elevation (Barbour et al. 1991). The red fir is considered a climax species, and shares climax status with white fir at the upper limit of the white fir distribution (Laacke 1990). The shift in dominance from white fir (*Abies concolor*) to red fir closely corresponds with the freezing level during months of maximum precipitation (Barbour et al. 1991). The shift in dominance to red fir may relate to snowpack characteristics and tolerance of red fir saplings to snowpack (Kunz 1988 cited in Barbour et al. 1990; Barbour et al. 1991), which are well adapted to heavy snows and ice (Gordon 1978).

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2. **Sensitivity of component species.**
    a. Sensitivity of component species to climate change: High
        i. Participant confidence: Moderate

Additional comments: Hemlock and white fir are likely better suited to future climate changes as the density of large red fir has decreased by 50%. Higher mortality in smaller diameter red fir likely reflects warming and drying conditions. Red fir does best in well-developed, well-drained gravelly-loam soils, but also tolerates shallow soils. Red fir is sensitive to competition with lodgepole pine and white fir, which may be relatively less sensitive to climatic changes.

References: The component species display distinct associations with soil moisture gradients. For example, within red fir forests throughout the Sierra Nevada, lodgepole pine occupies wet sites, whereas dry sites in the south may be shared with sugar pine (*P. lamberiana*), mountain hemlock (*Tsuga mertensiana*) and incense cedar (*Calocedrus*) (Laacke 1990; North et al. 2002). The association between

El Niño events and red fir recruitment may be related to enhanced winter snowpack increasing soil moisture levels (Barbour et al. 1991; North et al. 2005). For example, Barbour et al. (1990) found that red fir and white fir seedlings established differentially in response to soil moisture. White fir were favored in open/xeric microhabitats, whereas red fir were favored in open/mesic microhabitats (Barbour et al 1990). The soil 20 cm below the surface of a red fir site in Stanislaus National Forest contained 50% moisture (percent dry weight) in late May and 17% in late August, while similar texture soil beneath the white fir site contained only 28% and 10% respectively (Barbour et al. 1990). In comparison, on steep slopes where soils are shallowest, red fir growth is poor and stands are open (Laacke 1990). At lower elevations, red fir is associated with riparian areas (North et al. 2002).

White fir may be better suited to adapt to the impacts of climate change relative to the red fir (Laacke and Tappeiner 1996), and white fir growth more closely follows trends in climate (Hurteau et al. 2007). In the Pacific Northwest, lodgepole pine grow best at sites with significant spring frost, summer temperatures averaging <15^{o} C, and soils that fully recharge from snowmelt (Coops and Waring 2011).

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3. Sensitivity to changes in disturbance regimes.

a. Sensitivity to disturbance regimes including: Wildfire, drought, insects, disease
b. Sensitivity to these disturbance regimes: High
    i. Participant confidence: Moderate

Additional comments: Insect and disease issues include dwarf mistletoe (infects 40% of trees) and annosus root rot (a problem in dense stands). Drought may be an important, negative controlling agent of red fir regeneration after fire.

References:

Wildfire: Fire effects on red fir forests are generally poorly understood (Caprio 2000; see Long et al. 2013 for a discussion of relevant fire research). See Long et al. 2013 for a discussion of relevant research. It has both been suggested that upper montane red fir forests are not fire dependent (Barbour et al. 1990) and that fire was a major historic element in creating small openings in dense forests and preparing seedbeds for regeneration (Chappell and Agee 1996; Laacke and Tappeiner 1996). Historically, fire frequency in the red fir forest occurred at >50-year intervals (Pitcher 1987). Red fir forests were dominated by low- and moderate-intensity fires, resulting in small, scattered groups of regeneration (Kilgore 1971, Kilgore 1973, Agee 1990, and Taylor 1993 cited in Laacke and Tappeiner 1996; Taylor and Halpern 1991) and a patchwork of ages in trees (Kane et al. 2013), as red fir seedlings often take 3 to 4 years to establish after fire (Chappell and Agee 1996). Reconstructed regeneration patterns in Sequoia National Park indicate that red fir regeneration can be delayed 60 years following fire, with the delay attributed to variations in fire behavior (Pitcher 1987). Intense fires, however, result in high mortality of red firs (Kane et al. 2013). Fire suppression policy instated in the early 1900s has reduced the fire frequency in these forests (Van de Water and Safford 2011). Reduced fire frequency can increase forest density and shift the forest composition to less fire tolerant species and more shade tolerant species (Bouldin 1999; Safford 2010)

Pathogens: Pathogens and pests, including dwarf mistletoe (*Arceuthobium abietinum f. sp. magnificae*), bark beetle (*Scolytus ventralis*), and root disease (*Heterobasidion annosum*) are major causes of fir mortality, while others, including broom rust (*Melamsporella caryophyllacearum)*, trunk rot (*Echinodontium tinctorium*), and Douglas fir-tussock moth (*Orygia pseudotsgata*) have been shown to cause growth loss in the Teakettle Experimental Forest in the Sierra Nevada (Laacke 1990; North et al. 2002). Dwarf mistletoe infection and decay of red fir stands, however, may be important for wildlife (Laacke and Tappeiner 1996). The fir engraver, a bark beetle, is found throughout the range of red fir and usually preys upon trees in conjunction with a disease or fire damage (Laacke 1990). Red and white fir can be infested by the fir engraver beetle while lodgepole and ponderosa pine can be infested by the mountain pine beetle (Living Assessment 2013).

A 2006 model estimated that 1.4 million acres (566,560 ha) of Sierra Nevada forest is 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 (Living Assessment 2013). In contrast, others have reported that insect infestations are relatively rare in the red fir forest (Laacke and Tappeiner 1996).

Drought: Red fir appears to be more sensitive to drought than white fir, but red fir also exhibits poor growth in water-logged soils (Laacke 1990). Pest pressure can increase tree sensitivity to drought (Waring et al. 1987).

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

a. Sensitivity to climate and climate-driven changes including: Altered fire regimes, evapotranspiration and soil moisture, altered hydrology
b. Sensitivity to these climate and climate-driven changes: High
    i. Participant confidence: Moderate

Additional comments: Red fir is sensitive to snowpack boundary, so as snow retreats, red fir stands will likely shift to cooler north slopes and move upward. However, soil constraints (e.g., moisture, nutrients) may limit movement in both (north and upslope) directions.

References:
Altered snowpack and hydrology: Red fir is considered to be a climax species, which dominates in areas with high average snowpack on April 1 (Barbour et al. 1991), and whose recruitment is associated with occurrence of El Niño events (North et al. 2005). In general, the southern portion of the Sierra Nevada forest has seen an increase in April 1 snowpack while the northern portion has seen a general decrease in snowpack from 1950-1997; however, there is a high degree of spatial heterogeneity (Moser et al. 2009).

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5. Sensitivity to impacts of other non-climate stressors.

a. Sensitivity to other non-climate stressors including: Other – Altered interspecific interactions
b. Current effects of these identified stressors on system: Low
    i. Participant confidence: Moderate
c. Degree stressors increase sensitivity to climate change: Moderate
    i. Participant confidence: Moderate

Additional comments: Red fir is sensitive to non-climatic stressors that may increase its sensitivity to climate change, including recreation and water diversion, which alter soil moisture and the sediment regime. These non-climate stressors may exacerbate and/or accelerate climate impacts on red fir systems. Although red fir forests have not been historically logged, recently their harvest has become more common because their wood is very valuable. Some participants thought that increased timber extraction may accelerate sensitivity of the red fir system to climate change, however the literature is mixed. Pocket gophers (*Thomomys* sp.) reduce the establishment of red fir.

References: Red fir forests were historically not heavily logged in the Sierra Nevada because they were far from timber markets and located on inaccessible terrain (Laacke and Tappeiner 1996). Pocket gophers 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 (Laacke 1990; Laurent et al. 1994).

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6. Other sensitivities.

a. Other critical sensitivities not addressed: See additional comments
   i. Participant confidence: Moderate
b. Collective degree these factors increase system sensitivity to climate change: Moderate

Additional comments: Other sensitivities include genetic bottlenecks and lack of appropriate soils in future climate space. Genetic bottlenecks may occur due to invasion of lodgepole and white fir, as well as fragmentation of habitat. Soils may not align with climate bands that could support red fir in the future, which could result in the red fir forest becoming more fragmented and persisting in discrete patches, making it vulnerable to disturbances other than climate (e.g. wildfire, road building, etc.).

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7. Overall user ranking.

a. Overall sensitivity of this system to climate change: High
   i. Participant confidence: High

Additional comments: High sensitivity due to increased temperature, decreased snowpack, longer drought-affected soils, invasion by white fir and lodgepole pine, and non-climate stressors such as pocket gophers, insects, and mistletoe.

Adaptive Capacity

1. **System extent and integrity.**
    a. System extent throughout the Sierra Nevada (e.g. widespread to narrow distribution): Moderate
        i. Participant confidence: High
    b. Level of fragmentation across the Sierra Nevada: Moderate
        i. Participant confidence: Moderate

Additional comments: Range of the red fir ecosystem is restricted to elevations between 1676-2134 m (5500-7000 feet). Red fir system exists in fragmented patches generally at elevations above 1829 m (6000 ft), and fragmentation is influenced by white fir and lodgepole pine. The system has limited ability to shift upslope.

References:

Geographic extent: Red fir forests occupy roughly 838,905 acres (339,492 ha) in the Sierra Nevada, 11% of the region's 7.8 million acres (3.1 million ha) (Long et al. 2013). Red fir exists in fragmented patches in a relatively narrow elevational band (approximately 6000 ft to 9000 ft (1829 m to 2743 m) (Laacke 1990; North et al. 2002). Red fir can also be found at lower elevations in canyons and cool riparian zones (Laacke 1990). From 1935 to 1992, the red fir forest subtype and the red fir-white fir forest subtype increased in landscape percent across the northern half of the Sierra Nevada by 8.9% and 2.5%, respectively. In contrast, the red fir-Jeffrey pine and red fir-western white pine forest subtypes have decreased in landscape percent by 6.3% and 5.1%, respectively. It is hypothesized that the Jeffrey pine and western white pine populations were replaced by more shade tolerant species such as mountain hemlock (Bouldin 1999). From 1935 to 1992, white fir-mixed conifer forests increased by 19.1% in the northern half of the Sierra Nevada (Bouldin 1999).

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2. **Resistance, recovery, and refugia.**
    a. Ability of system to resist or recover from impacts: Moderate
        i. Participant confidence: Moderate
    b. Suitable microclimates within the system that could support refugial communities: While red fir is susceptible to change at the landscape scale, examples of red fir receding and recovering under oscillating cold/dry and cool/wet periods support that it has persisted under past changing climate conditions.

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3. **Landscape permeability.**
    a. Degree of landscape permeability: Low
        i. Participant confidence: Moderate
    b. Potential types of barriers to dispersal that apply: Geologic features, arid lands

Additional comments: Red fir is restricted to cool/moist climates with significant snowpack. Adequate soils may be limited in the new elevations that will support the appropriate temperature bands and moisture for the red fir system.

References: Red firs produce heavy seed crop sufficient for reliable regeneration every 1 to 4 years, after sexual maturity is reached after 35-45 years (Laacke 1990); more mature trees tend to produce more seeds. Seeds are distributed by wind as cones disintegrate, usually in late September and mid-October. Dispersal distance of California red fir seeds is usually 1.5 to 2 times the tree's height (Laacke 1990).

4. System diversity.

a. Level of physical and topographic diversity: High
    i. Participant confidence: Moderate
b. Level of component species/functional group diversity: Low
    i. Participant confidence: Moderate
c. Description of diversity: System includes lodgepole pine, mountain hemlock, white fir, noble fir, and red fir. It appears that lodgepole pine, hemlock, white fir, and noble fir are better able to adjust to climatic changes than red fir, although red fir has been able to persist for thousands of years under changing climate conditions.

References:

Community structure: Red fir forests may be able to extend their 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. 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 2004).

5. Management potential.

a. Value level people ascribe to this system: High
    i. Participant confidence: High
b. Specificity of rules governing management of the system: High
    i. Participant confidence: High
c. Description of use conflicts: There is not strong development pressure though there is potential of increased human activity with warming climate.
d. Potential for managing or alleviating climate impacts: Potential strategies include thinning of early seral stands to improve health and reduce mortality, managing for a variety of seral stages using the healthiest stands, and avoiding water diversions and other infrastructure that could modify groundwater patterns and flows.

6. Other adaptive capacity factors.

a. Additional factors affecting adaptive capacity: See comments below
    i. Participant confidence: High
b. Collective degree these factors affect the adaptive capacity of the system: High

Additional comments: It may be difficult to implement some management strategies (e.g., those related to fire) due to low social and/or political feasibility.

7. Overall user ranking.

a. Overall adaptive capacity of the system: Low
    i. Participant confidence: Moderate

Additional comments: Red fir will likely persist but warming, drying, longer summers, and more wildfire are all potential stressors to the detriment of the red fir system.

Exposure

1. Exposure factors[8].

a. Factors likely to be most relevant or important to consider for the system: Temperature, precipitation, climatic water deficit, wildfire, snowpack, shifts in vegetation structure

i. Participant confidence: Moderate-High (temperature); Low-Moderate (precipitation); Low-Moderate (climatic water deficit); Moderate (wildfire); High (snowpack); High (vegetation)

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2. Exposure by region.

a. Overall exposure for different Sierra Nevada regions: North – Moderate-High; Central – Moderate-High; South – Moderate

i. Participant confidence: Moderate (all)

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3. Overall user ranking.

a. Overall exposure of the species to climate changes: High

i. Participant confidence: Moderate

References:

Distribution: A predominant effect of climate change in the Sierra Nevada regions will likely result in loss of red fir/lodgepole pine communities, especially at higher elevations (PRBO Conservation Science 2011). Based on other climate scenarios, lodgepole pine distributions in California are predicted to increase slightly to 2020 then decrease significantly by the end of the century (Miller 2003).

Temperature: Over the next century, temperatures in California are expected to rise (Hayhoe et al. 2004: Cayan et al. 2008), with the lower range of warming projected between 1.7-3.0°C, 3.1-4.3°C in the medium range, and 4.4-5.8°C in the high range (Cayan et al. 2008). Temperatures along the western slope of the Sierra Nevada are forecast to increase between 0.5-1°C by 2049, and 2-3°C by 2099 (Das et al. 2011). 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; Geos Institute 2013). Temperature projections using global coupled ocean-atmospheric models (GDFL[9] and PCM[10]) predict summer temperatures to increase 1.6-2.4˚C by mid- century (2049), with the least increases expected in the northern bioregion, and greatest increases expected in the southern bioregion (Geos Institute 2013). By late century (2079), summer temperatures are forecast to increase 2.5-4.0˚C, with changes of least magnitude occurring in the central bioregion (Geos Institute 2013). Winter temperatures are forecast to increase 2.2-2.9˚C by late century (2079), with changes of least magnitude occurring 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). Projections for future precipitation in the Sierra Nevada vary among models; some demonstrate little to no change (e.g. PCM) while others demonstrate more substantial changes (e.g. GFDL). In general, annual precipitation is

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[8] Participants were asked to identify exposure factors most relevant or important to the species but were not asked to evaluate the degree to which the factor affects the species.

[9] Delworth, T. L., Broccoli, A. J., Rosati, A. et al. (2006) GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics. Journal of Climate, 19:643-674.

[10] Washington, W. M., Weatherly J. W., Meehl G. A. et al. (2000) Parallel climate model (PCM) control and transient simulations. Climate Dynamics 16:755-744.

projected to exhibit only modest changes by the end of the century (Hayhoe et al. 2004; Dettinger 2005; Maurer 2007; Cayan et al. 2008; Geos Institute 2013), with some precipitation decreases in spring and summer (Cayan et al. 2008; Geos Institute 2013). Frequency of extreme precipitation, however, is expected to increase in the Sierra Nevada between 11-49% by 2049 and 18-55% by 2099 (Das et al. 2011).

Snow volume and timing: Overall, April 1st snowpack in the Sierra Nevada, calculated as snow water equivalent (SWE), has seen a reduction of 11% in the last 30 years (Flint et al. 2013), as a consequence of earlier snowmelt (Cayan et al. 2001; Stewart et al. 2005; Hamlet et al. 2007), increased frequency of melt events (Mote et al. 2005), and increased rain:snow ratio (Knowles et al. 2006). However, trends in snowpack in the Sierra Nevada have displayed a high degree of interannual variability and spatial heterogeneity (Mote et al. 2005; Safford et al. 2012). SWE in the southern Sierra Nevada has actually increased during the last half-century, due to increases in precipitation (Mote et al. 2005; Mote 2006; Moser et al. 2009; Flint et al. 2013).

Despite modest projected changes in overall precipitation, models of the Sierra Nevada region largely project decreasing snowpack (Miller et al. 2003; Dettinger et al. 2004b; Hayhoe et al. 2004; Knowles and Cayan 2004; Maurer 2007; Young et al. 2009) and earlier timing of runoff center of mass (Miller et al. 2003; 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, 2004b; Young et al. 2009; Null et al. 2010).

Annual snowpack in the Sierra Nevada is projected to decrease between 64-87% by late century (2060-2079) (Thorne et al. 2012; Flint et al. 2013; Geos Institute 2013). Under scenarios of 2-6˚C warming, snowpack is projected to decline 10-25% at elevations above 3750 m (12303 ft), and 70-90% below 2000 m (6562 ft) (Young et al. 2009). Several models project greatest losses in snowmelt volume 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), because snowfall is comparatively light below that elevation, and above that elevation, snowpack is projected to be largely retained. The greatest declines in snowpack are anticipated for the northern Sierra Nevada (Safford et al. 2012), with the current patterns of snowpack retention in higher-elevation southern Sierra Nevada basins expected to continue through the end of the century (Maurer 2007).

Average fractions of total precipitation falling as rain in the Sierra Nevada can be expected to increase by approximately 10% under a scenario of 2.5˚C warming (Dettinger et al. 2004b). Increased rain:snow ratio and advanced timing of snowmelt initiation are expected to advance the runoff center of mass by 1-7 weeks by 2100 (Maurer 2007), although advances will likely be non-uniformly distributed in the Sierra Nevada (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: 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). 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. 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 projections using the Basin Characterization Model

(Thorne et al. 2012; Flint et al. 2013) and IPCC A2 emissions scenario predict increased water deficits (i.e., decreased soil moisture) by up to 44% in the northern Sierra Nevada, 38% in the central Sierra Nevada, and 33% in the southern Sierra Nevada (Geos Institute 2013). The change in water deficit from present to future (2020-2049) climate for Yosemite National Park (YNP) is projected to exceed a 25% increase for plots occupied by red fir, lodgepole pine, western juniper, whitebark pine, western white pine, giant sequoia and mountain hemlock (Lutz et al. 2010). 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 (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).

Wildfire: 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). Increasing temperatures and earlier snowmelt in the Sierra Nevada have been correlated with an increase in large (>1000 acre) extent fire since the 1980s (Westerling and Bryant 2006). Between 1972-2003, years with early arrival of spring conditions accounted for 56% of wildfires and 72% of area burned in the western U.S., as opposed to 11% of wildfires and 4% of area burned in years with a late spring (Westerling et al. 2006; Geos Institute 2013). Fire severity also rose from 17% to 34% high severity (i.e. stand replacing) from 1984-2007, especially in middle elevation conifer forests (Miller et al. 2009).

Fire activity within the Sierra Nevada is influenced by distinct climate patterns and diverse topography. Higher fire activity is weakly associated with El Niño (warm) conditions in parts of the southern Cascades (Taylor et al. 2008) and northern Sierra Nevada (Valliant and Stephens 2009 cited in Taylor and Scholl 2012), while in Yosemite National Park (YNP) large fires are associated with La Niña (cool) conditions, which are characteristically drier (Taylor and Scholl 2012). Some evidence suggests that fire frequency is higher on southern aspect than northern aspect slopes in mid- and upper-montane forests (Taylor 2000); however, in YNP mixed conifer forests, no spatial trend in fire frequency was found (Scholl and Taylor 2010). Burn condition heterogeneity may promote different forest understory responses in mixed conifer forests across a landscape, with lower intensity burns promoting tree regeneration, and higher intensity or more frequent burns creating shrub habitat (Lydersen and North 2012).

Reconstruction of pre-suppression fire regimes using fire scars indicates that years with widespread fires in dry pine and mixed conifer forests are strongly related to drought in YNP (Taylor and Scholl 2012), other sites in California (Taylor and Beaty 2005; Taylor et al. 2008), and the southwest U.S. (Swetnam and Betancourt 1998, Sakulich and Taylor 2007 cited in Taylor and Scholl 2012). Current year drought combined with antecedent wet years with increased production of fine fuels are associated with fire in the southwest U.S. (Swetnam and Betancourt 1990, McKenzie et al. 2004 cited in Strom and Fule 2007) as well as at some sites in the Sierra Nevada (Taylor and Beaty 2005), but not in YNP, suggesting that "heterogeneity of forest floor vegetation may influence the temporal structure of fire-climate relationships, even at local scales" (Taylor and Scholl 2012).

Large fire occurrence and total area burned in California are predicted to continue increasing over the next century, with total area burned increasing 7-41% by 2050, and 12-74% by 2085 (Westerling et al. 2011). Models by Westerling et al. (2011) project annual area burned in the northern, central and southern Sierra Nevada to increase by 67-117%, 59-169%, and 35-88%, respectively (Geos Institute 2013). Greatest increases in area burned in the Sierra Nevada are projected to occur at mid-elevation sites along the west side of the range (Westerling et al. 2011).

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).

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).

We acknowledge the Template for Assessing Climate Change Impacts and Management Options (TACCIMO) for its role in making available their database of climate change science to support this exposure assessment. Support of this database is provided by the Eastern Forest & Western Wildland Environmental Threat Assessment Centers, USDA Forest Service.

Literature Cited

Anderson, R. S. (1990). "Holocene forest development and paleoclimates within the central Sierra Nevada, California." Journal of Ecology **78**: 470-489.

Anderson, R. S. (2004). Response of Sierra Nevada Vegetation and Fire Regimes to Past Climate Changes. US Department of Agriculture Forest Service Pacific Southwest Research Station. **PSW-GTR-193:** 47-50.

Barbour, M. G., N. H. Berg, T. G. F. Kittel and M. E. Kunz (1991). "Snowpack and the Distribution of a Major Vegetation Ecotone in the Sierra Nevada of California." Journal of Biogeography **18**(2): 141-149.

Barbour, M. G., B. M. Pavlik and J. A. Antos (1990). "Seedling Growth and Survival of Red and White Fir in a Sierra Nevada Ecotone." America Journal of Botany **77**(7): 927-938.

Bouldin, J. (1999). Twentieth Century Changes in Forests of the Sierra Nevada Mountains. PhD, University of California, Davis.

Caprio, A., ed. (2000). 1999 Annual Fire Report: Research, Inventory, and Monitoring. 1999 Annual Fire Report: Research, Inventory, and Monitoring. A. Caprio, Sequioa and Kings Canyon National Parks.

Cayan, D., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio and D. H. Peterson (2001). "Changes in the Onset of Spring in the Western United States." Bulletin of the American Meteorological Society **82**(3): 399-145.

Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree and K. Hayhoe (2008). "Climate change scenarios for the California region." Climatic Change **87**(S1): 21-42.

Chappell, C. B. and J. K. Agee (1996). "Fire Severity and Tree Seedling Establishment in Abies Magnifica Forests, Southern Cascades, Oregon." Ecological Applications **6**(2): 628-640.

Coops, N. C. and R. H. Waring (2011). "A process-based approach to estimate lodgepole pine (Pinus contorta Dougl.) distribution in the Pacific Northwest under climate change." Climatic Change **105**(1-2): 313-328.

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

Das, T., M. D. Dettinger, D. R. Cayan and H. G. Hidalgo (2011). "Potential increase in floods in California's Sierra Nevada under future climate projections." Climatic Change **109**(S1): 71-94.

Dettinger, M. D. (2005). "From climate-change spaghetti to climate-change distributions for 21st Century California." San Francisco Estuary and Watershed Science **3**(1): Article 4.

Dettinger, M. D., D. R. Cayan, N. Knowles, A. Westerling and M. K. Tyree (2004a). Recent Projections of 21st-Century Climate Change and Watershed Responses in the Sierra Nevada, USDA Forest Service. **Gen. Tech. Report PSW-GTR-193**.

Dettinger, M. D., D. R. Cayan, M. K. Meyer and A. E. Jeton (2004b). "Simulated Hydrologic Responses to Climate Variations and Change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099." Climate Change **62**: 283-317.

Flint, L. E., A. L. Flint, J. H. Thorne and R. Boynton (2013). "Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance." Ecological Processes ***2***: 25.

Geos Institute (2013). Future Climate, Wildfire, Hydrology, and Vegetation Projections for the Sierra Nevada, California: A climate change synthesis in support of the Vulnerability Assessment/Adaptation Strategy (VAAS) process, Available online at: http://www.geosinstitute.org/climatewiseservices/completed-climatewise-projects.html.

Gonzalez, P., J. J. Battles and K. M. Waring (2009). OOS 30-8: Climate change and the detection of possible elevation shifts of forest species in the Sierra Nevada, California. The 94th ESA Annual Meeting. Albuquerque, NM.

Gordon, D. R., J. M. Welker, J. M. Menke and K. J. Rice (1989). "Competition for soil water between annual plants and blue oak (*Quercus douglasii*) seedlings." Oecologia **79**(4): 533-541.

Gordon, D. T. (1978). "California Red Fir Literature: Some Corrections and Comments." Forest Science **24**(1): 52-56.

Hamlet, A. F., P. W. Mote, M. P. Clark and D. P. Lettenmaier (2007). "Twentieth-Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western United States*." Journal of Climate **20**(8): 1468-1486.

Hayhoe, K., D. Cayan, C. B. Field, P. C. Frumhoff, E. P. Maurer, N. L. Miller, S. C. Moser, S. H. Schneider, K. N. Cahill, E. E. Cleland, L. Dale, R. Drapek, R. M. Hanemann, L. S. Kalkstein, J. Lenihan, C. K. Lunch, R. P. Neilson, S. C. Sheridan and J. H. Verville (2004). "Emissions pathways, climate change, and impacts on California." Proceedings of the National Academy of Sciences **101**(34): 12422-12427.

Hurteau, M., H. Zald and M. North (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**(9): 1681-1691.

Kane, V. R., J. A. Lutz, S. L. Roberts, D. F. Smith, R. J. McGaughey, N. A. Povak and 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.

Knowles, N. and D. Cayan (2004). "Elevational dependence of projected hydrologic changes in the San Francisco Estuary and Watershed." Climate Change **62**: 319-336.

Knowles, N., M. D. Dettinger and D. Cayan (2006). "Trends in Snowfall versus Rainfall in the Western United States." Journal of Climate **19**(18): 4545-4559.

Laacke, R. J. (1990). *Abies magnifica* A. Murr., California red fir. Silvics of North America. R. M. Burns and B. H. Honkala**:** 71.

Laacke, R. J. and J. C. Tappeiner (1996). Red Fir Ecology and Management, Sierra Nevada Ecosystem Project (SNEP). Regents of the University of California.

Laurent, T. E., R. C. Graham and K. R. Tice (1994). "Soils of the Red Fir Forest-Barrens Mosaic, Siskiyou Mountains Crest, California." Soil Science Society of America Journal **58**(6): 1747-1752.

Living Assessment. (2013). "Chapter 2 Bio-region: Sierra Nevada bio-region." Retrieved Feb. 28 2013, from http://livingassessment.wikispaces.com/Chapter+2+Bio-region.

Long, J., C. Skinner, M. North, P. Winter, W. Zielinski, C. Hunsaker, B. Collins, J. Keane, F. Lake, J. Wright, E. Moghaddas, A. Jardine, K. Hubbert, K. Pope, A. Bytnerowicz, M. Fenn, M. Busse, S. Charnley, T. Patterson, L. Quinn-Davidson, H. Safford, chapter authors and Synthesis team members, R. Bottoms, J. Hayes, team coordination and review, M. Meyer, D. Herbst, K. Matthews and additional contributors (2013). Science Synthesis to Support Land and Resource Management Plan Revision in the Sierra Nevada and Southern Cascades. USDA Forest Service Pacific Southwest Research Station. Albany, CA**:** 504. Available at: http://www.fs.fed.us/psw/publications/reports/psw_sciencesynthesis2013/index.shtml.

Lutz, J. A., J. W. van Wagtendonk and J. F. Franklin (2010). "Climatic water deficit, tree species ranges, and climate change in Yosemite National Park." Journal of Biogeography **37**: 936-950.

Lydersen, J. and M. North (2012). "Topographic Variation in Structure of Mixed-Conifer Forests Under an Active-Fire Regime." Ecosystems **15**(7): 1134-1146.

Maurer, E. P. (2007). "Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios." Climatic Change **82**(3-4): 309-325.

Maurer, E. P., I. T. Stewart, C. Bonfils, P. B. Duffy and D. Cayan (2007). "Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada." Journal of Geophysical Research **112**(D11).

McKenzie, D., Z. Gedalof, D. L. Peterson and P. W. Mote (2004). "Climate Change, Wildfire, and Conservation." Conservation Biology **18**(4): 890-902.

Miller, C. (2003). Simulation of effects of climatic change on fire regimes. Fire and climatic change in temperate ecosystems of the western Americas. T. T. Veblen, W. L. Baker, G. Montenegro and T. W. Swetnam, Springer**:** 69-94.

Miller, J. D., H. D. Safford, M. Crimmins and A. E. Thode (2009). "Quantitative Evidence for Increasing Forest Fire Severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA." Ecosystems **12**: 16-32.

Miller, N. L., K. E. Bashford and E. Strem (2003). "Potential impacts of climate change on California hydrology." Journal of American Water Resources Association **39**(4): 771-784.

Moser, S. C., G. Franco, S. Pittiglio, W. Chou and D. Cayan (2009). The Future Is Now: An Update On Climate Change Science Impacts And Response Options For California, Prepared for: California Energy Commission, Public Interest Energy Commission. **CEC-500-2008-071**.

Mote, P. W. (2006). "Climate-Driven Variability and Trends in Mountain Snowpack in Western North America." Journal of Climate **19**(23): 6209-6220.

Mote, P. W., A. F. Hamlet, M. P. Clark and D. P. Lettenmaier (2005). "Declining Mountain Snowpack in Western North America*." Bulletin of the American Meteorological Society **86**(1): 39-49.

Murdock, T. Q., S. W. Taylor, A. Flower, A. Mehlenbacher, A. Montenegro, F. W. Zwiers, R. Alfaro and D. L. Spittlehouse (2013). "Pest outbreak distribution and forest management impacts in a changing climate in British Columbia." Environmental Science & Policy **26**: 75-89.

North, M., M. Hurteau, R. Fiegener and M. Barbour (2005). "Influence of Fire and El Niño on Tree Recruitment Varies by Species in Sierran Mixed Conifer." Forest Science **51**(3): 187-197.

North, M., B. Oakley, J. Chen, H. Erickson, A. Gray, A. Izzo, D. Johnson, S. Ma, J. Marra, M. Meyer, K. Purcell, T. Rambo, D. Rizzo, B. Roath and T. Schowalter (2002). Vegetation and Ecological Characteristics of Mixed-Conifer and Red Fire Forests at the Teakettle Experimental Forest. US Department of Agriculture Forest Service Pacific Southwest Research Station. Albany, CA. **PSW-GTR-186:** 52.

Null, S. E., J. H. Viers and J. F. Mount (2010). "Hydrologic response and watershed sensitivity to climate warming in California's Sierra Nevada." PLoS One **5**(4).

Pitcher, D. C. (1987). "Fire history and age structure in red fir forests of Sequoia National Park, California." Canadian Journal of Forest Research **17**(7): 582-587.

PRBO Conservation Science (2011). Projected Effects of Climate Change in California: Ecoregional Summaries Emphasizing Consequences for Wildlife. **Version 1.0:** 68. Available at http://data.prbo.org/apps/bssc/uploads/Ecoregional021011.pdf.

Safford, H. (2010). A summary of current trends and probable future trends in climate and climate-driven processes in the Giant Sequoia National Monument and the neighboring Sierra Nevada, USDA Forest Service, Pacific Southwest Region**:** 17. Available online at: http://www.fs.fed.us/r15/sequoia/gsnm/climate_trends_Monument.pdf.

Safford, H., M. North and M. D. Meyer (2012). Chapter 3: Climate Change and the Relevance of Historical Forest Condition. Managing Sierra Nevada Forests, USDA Forest Service, Pacific Southwest Research Station. **Gen. Tech. Rep. PSW-GTR-237**.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. P. Huang, N. Harnik, A. Leetmaa, N. C. Lau, C. Li, J. Velez and N. Naik (2007). "Model projections of an imminent transition to a more arid climate in southwestern North America." Science **316**(5828): 1181-1184.

Sheffield, J., G. Goteti, F. Wen and E. F. Wood (2004). "A simulated soil moisture based drought analysis for the United States." Journal of Geophysical Research: Atmospheres (1984-2012) **109(D24)**.

Stewart, I., D. Cayan and M. D. Dettinger (2005). "Changes toward Earlier Streamflow Timing across Western North America." Journal of Climate **18**: 1136-1155.

Strom, B. and P. Z. Fule (2007). "Pre-wildfire fuel treatments affect long-term ponderosa pine forest dynamics." International Journal of Wildland Fire **16**: 128-138.

Taylor, A. H. (2000). "Fire Regimes and Forest Changes in Mid and Upper Montane Forests of the Southern Cascades, Lassen Volcanic National Park, California, U.S.A." Journal of Biogeography **27**(1): 87-104.

Taylor, A. H. and R. M. Beaty (2005). "Climatic influences on fire regimes in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA." Journal of Biogeography **32**(3): 425-438.

Taylor, A. H. and C. B. Halpern (1991). "The structure and dynamics of Abies magnifica forests in the southern Cascade Range, USA." Journal of Vegetation Science **2**: 189-200.

Taylor, A. H. and A. E. Scholl (2012). "Climatic and human influences on fire regimes in mixed conifer forests in Yosemite National Park, USA." Forest Ecology and Management **267**: 144-156.

Taylor, A. H., V. Trouet and C. N. Skinner (2008). "Climatic influences on fire regimes in montane forests of the southern Cascades, California, USA." International Journal of Wildland Fire **17**: 60-71.

Thorne, J. H., R. Boynton, L. Flint, A. Flint and T.-N. G. Le (2012). Development and Application of Downscaled Hydroclimatic Predictor Variables for Use in Climate Vulnerability and Assessment Studies, Prepared for California Energy Commission, Prepared by University of California, Davis. **CEC-500-2012-010**.

Van de Water, K. M. and H. D. Safford (2011). "A Summary of Fire Frequency Estimates for California Vegetation before Euro-American Settlement." Fire Ecology **7**(3): 26-58.

Waring, R. H., K. J. Cromack, P. A. Matson, R. D. Boone and S. G. Stafford (1987). "Reponses to Pathogen-induced Disturbance: Decomposition, Nutrient Availability, and Tree Vigour." Forestry **60**(2): 219-227.

Westerling, A. L. and B. P. Bryant (2006). Climate Change and Wildfire in and around California: Fire Modeling and Loss Modeling. Prepared for California Climate Change Center. **CEC-500-2005-190-SF:** 33.

Westerling, A. L., B. P. Bryant, H. K. Preisler, T. P. Holmes, H. G. Hidalgo, T. Das and S. R. Shrestha (2011). "Climate change and growth scenarios for California wildfire." Climatic Change **109**(S1): 445-463.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan and T. W. Swetnam (2006). "Warming and earlier spring increase western U.S. forest wildfire activity." Science **313**: 940-943.

Young, C. A., M. I. Escobar-Arias, M. Fernandes, B. Joyce, M. Kiparsky, J. F. Mount, V. K. Mehta, D. Purkey, J. H. Viers and D. Yates (2009). "Modeling The Hydrology Of Climate Change In California's Sierra Nevada For Subwatershed Scale Adaptation." Journal of American Water Resources Association **45**(6): 1409-1423.

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