Focal Resource: WHITEBARK PINE

Taxonomy and Related Information

Whitebark pine (*Pinus albicaulis)*; Distribution Sierra Nevada-wide, although primarily in central and southern Sierra; patchy distribution in the north.

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[1]. The following document represents the vulnerability assessment results for the **WHITEBARK PINE**, 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[2].

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.

---

[1] 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.

[2] 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.

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

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: whether the species is a generalist or specialist; physiological sensitivity to temperature, precipitation, and other factors (e.g., pH, salinity); dependence on sensitive habitats; species' life history; sensitivity of species' ecological relationships (e.g., predator/prey, competition, forage); sensitivity to disturbance regimes (e.g., wind, drought, flooding); and sensitivity to non-climate stressors (e.g., grazing, recreation, infrastructure). Adaptive capacity elements include: dispersal ability and barriers to dispersal, phenotypic plasticity (e.g., can the species express different behaviors in response to environmental variation), species' potential to adapt evolutionarily to climate change, species' intraspecific/life history diversity (e.g., variations in age at maturity, reproductive or nursery habitat use, etc.), and species' value and management potential. To assess exposure, participants were asked to identify the climate and climate-driven changes most relevant to consider for the species 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[3]. 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*[4].

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*[4].

Recommended Citation

Hauptfeld, R.S., J.M. Kershner, and K.M. Feifel, eds. 2014. Sierra Nevada Individual Species Vulnerability Assessment Technical Synthesis: Whitebark Pine *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.

---

[3] 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.

[4] 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.

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

Table of Contents

Overview of Vulnerability Component Evaluations

SENSITIVITY

Sensitivity Factor	Sensitivity Evaluation	Confidence
Generalist/Specialist	**2 Between generalist & specialist**	**3 High**
Physiology	**3 High**	**3 High**
Habitat	**3 High**	**3 High**
Life History	**3 K-selection**	**3 High**
Ecological Relationships	**3 High**	**3 High**
Disturbance Regimes	**3 High**	**3 High**
Non-Climatic Stressors – Current Impact	**1 Low**	**3 High**
Non-Climatic Stressors – Influence Overall Sensitivity to Climate	**2 Moderate**	**3 High**
Other Sensitivities	**3 High**	**2 Moderate**

Overall Averaged Confidence (Sensitivity)[5]: High

Overall Averaged Ranking (Sensitivity)[6]: Moderate–High

ADAPTIVE CAPACITY

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Dispersal Ability	**3 High**	**3 High**
Barriers Affect Dispersal Ability	**1 High**	**3 High**
Plasticity	**1 Low**	**3 High**
Evolutionary Potential	**2 Moderate**	**2 Moderate**
Intraspecific Diversity/Life History	**1 Low**	**3 High**
Species Value	**1.5 Low-Moderate**	**3 High**
Specificity of Management Rules	**3 High**	**3 High**
Other Adaptive Capacities	**2 Moderate**	**3 High**

Overall Averaged Confidence (Adaptive Capacity)[5]: High

Overall Averaged Ranking (Adaptive Capacity)[6]: Moderate

EXPOSURE

Relevant Exposure Factor	Confidence
Temperature	**3 High**
Precipitation	**3 High**
Climatic water deficit	**2 Moderate**
Wildfire	**2 Moderate**
Snowpack	**3 High**

---

[5] Overall confidence is an average of the confidence column for sensitivity, adaptive capacity, and exposure, respectively.

[6] Overall sensitivity, adaptive capacity, and exposure are an average of the sensitivity, adaptive capacity, or exposure evaluation columns above, respectively.

Exposure Region	Exposure Evaluation (2010-2080)	Confidence
Northern Sierra Nevada	**2.5 Moderate–High**	**3 High**
Central Sierra Nevada	**2.5 Moderate–High**	**3 High**
Southern Sierra Nevada	**3 High**	**3 High**

Overall Averaged Confidence (Exposure)[5]: High

Overall Averaged Ranking (Exposure)[6]: Moderate–High

Sensitivity

1. Generalist/Specialist.

a. Where does species fall on spectrum of generalist to specialist: In between
    i. Participant confidence: High
b. Factors that make the species more of a specialist: Seed dispersal dependency, other – temperature/precipitation.

Additional comments: Distribution of whitebark pine is climate-driven.

2. Physiology.

a. Species physiologically sensitive to one or more factors including: Temperature, precipitation
b. Sensitivity of species' physiology to one or more factors: High
    i. Participant confidence: High

Additional comments: Very dependent on climate, including temperature, and particularly cold temperatures.

References: Whitebark pine responses to warming temperatures may vary. Warming throughout the 20th century in the southeastern Sierra Nevada was positively correlated with annual branch growth rates of whitebark pine (Millar et al. 2004). That warming period produced abundant vertical branches in latter-century krummholz whitebark pine thickets at the upper treeline, compared with the compact, flat-topped crowns displayed at the start of the century (Millar et al. 2004). In contrast, whitebark pines that experienced significant mortality from 2007-2010 at low-elevations in the subalpine zone also experienced warmer, albeit drier conditions relative to the regional species distribution (Millar et al. 2004). Dolanc et al. (2013a) studied whitebark pine growth responses to climate in the central Sierra Nevada and found that radial growth was positively correlated with higher winter precipitation and higher spring temperatures, however whitebark and other drier-site subalpine species were somewhat sensitive to climate drivers than species found in more mesic sites. Although whitebark pine has been described as abundant on drier inland slopes and largely absent from wetter areas throughout its native range (Arno and Hoff 1989), in some semiarid areas it is more common on comparatively cold and moist sites (Mathiasen 1998 cited in Fryer 2002). Precipitation in whitebark pine communities ranges from 24 to 63 inches per year (Weaver 2001 cited in Fryer 2002), the majority (~66%) of which falls as snow (Arno and Hoff 1989 cited in Fryer 2002). Temperature and water availability also influence reproduction. Studies report that reproduction is best when July day/night temperatures exceed 68˚/39˚F (20˚/4˚C), and there is no water stress (Weaver 2001 cited in Fryer 2002).

3. Sensitive habitats.

a. Species dependent on sensitive habitats including: Alpine/subalpine
b. Species dependence on one or more sensitive habitat types: High
    i. Participant confidence: High

Additional comments: See comment above.

4. Life history.

a. Species reproductive strategy: K-selection
    i. Participant confidence: High
b. Species polycyclic, iteroparous, or semelparous: Iteroparous

Additional comments: Stand-wide and population-wide production of cones can be episodic in some areas.

---

5. **Ecological relationships.**
    a. Sensitivity of species' ecological relationships to climate change including: Hydrology, competition, other – dispersal agents
    b. Types of climate and climate-driven changes that affect these ecological relationships including: Precipitation
    c. Sensitivity of species to other effects of climate change on its ecology: High
        i. Participant confidence: High

Additional comments: Competition with lodgepole pine, red fir, and mountain hemlock.

---

6. **Disturbance regimes.**
    a. Disturbance regimes to which the species is sensitive include: Wildfire, insects, disease
    b. Sensitivity of species to one or more disturbance regimes: High
        i. Participant confidence: High

Additional comments: Whitebark pine is sensitivity to disturbance regimes including insects (e.g., very susceptible to the pine beetle), disease (e.g., white pine blister rust, particularly in the northern Sierra), and wildfire (i.e., in higher density stands at lower elevations).

References: Whitebark pine responses to fire are also complex, and little is known about the relationship between whitebark pine and fire in California, where stands tend to be much less dense than in the well-studied Rocky Mountain populations. Whitebark pine communities have a mixed-severity fire regime of widely ranging fire intensities and frequencies; fire-return intervals range from 30 to greater than 350 years (Arno and Hoff 1989; Agee 1994, Barrett 1994, Morgan et al. 1994 cited in Fryer 2002). Fire may support whitebark pine recruitment and establishment by preparing seedbeds (Vogl and Ryder 1969, McCaughey 1990 cited in Fryer 2002), reducing competition (McCaughey 1994 cited in Fryer 2002), and creating forest openings for Clark's nutcracker (*Nucifraga columbiana*) seed caching (Tomback 1982 cited in Fryer 2002). Higher-severity fires may actually better prepare seedbeds than low-severity fires (McCaughey 1990, Vogl and Ryder 1969 cited in Fryer 2002). Although survivorship is considered best on burned sites (McCaughey 1990 cited in Fryer 2002), very hot fires may retard seedling establishment for several decades (Arno 1980), and surface and crown fires of moderate intensity may kill large mature trees (Barmore et al. 1976, Keane and Arno 2001, Morgan and Bunting 1990 cited in Fryer 2002).

---

7. **Interacting non-climatic stressors.**
    a. Other stressors that make the species more sensitive include: Commercial development, invasive and other problematic species
    b. Current degree to which stressors affect the species: Low
        i. Participant confidence: High
    c. Degree to which non-climate stressors make species more sensitive: Moderate
        i. Participant confidence: High

Additional comments: Participants classified outdoor recreation (e.g., ski areas) as commercial development.

References: Whitebark pine is experiencing the most significant ongoing mortality episode in subalpine forests of western North America (Millar et al. 2012), in which mortality trends have increased since 1998 (Gibson et al. 2008 cited in Millar et al. 2012). The primary reason for these declines has been attributed to mountain pine beetles (*Dendroctonus ponderosae* Hopkins) and blister rust (*Cronartium ribicola*) (Tomback and Achuff 2010). In contrast to reported low-levels of mountain pine beetle mortality in California from 1998-2005 (Gibson et al. 2008 cited in Millar et al. 2012), a major mortality event occurred in eastern California from 2007-2010 (Millar et al. 2012), and expanding centers of pine beetle-caused mortality are currently found in the Warner Mountains and parts of the Inyo National Forest. Mountain pine beetle infestations often occur in conjunction with other pathogens, insects and environmental stressors, such as drought. Pest pressure can increase tree sensitivity to drought (Waring et al. 1987), and drought combined with increasing minimum temperatures, may enhance infestation of pine beetles in whitebark and limber pines (Millar et al. 2010). Warming temperatures may also facilitate an upward elevational shift of mountain pine beetle populations into whitebark pine habitats (Logan et al. 1995, Logan and Powell 2001 cited in Fryer 2002; Bentz et al. 2010).

Whitebark pines in the western U.S. are also sensitive to the exotic pathogen white pine blister rust (Tomback and Achuff 2010). Although infected trees may not die for several decades, white pine blister rust inhibits the trees' ability to produce seeds (Arno and Hoff 1989). White pine blister rust can also increase whitebark pine susceptibility to beetle-related mortality (Tomback and Achuff 2010). Field surveys in high-elevation forests in 2004-2006 found white pine blister rust in 24% of whitebark pine in the northern Sierra Nevada, and the pathogen is spreading southward in California (Maloney 2011). Currently, white pine blister rust does not appear to be advancing into upper subalpine zones (Millar et al. 2012). However, spread of white pine blister rust may have been limited by climate conditions (Dolanc et al. 2013b), and extended growing seasons may facilitate uphill expansion.

---

8. Other sensitivities.

a. <u>Other critical sensitivities not addressed</u>: Relies on Clark's nutcracker for dispersal
    i. Participant confidence: Moderate
b. <u>Collective degree these factors increase species' sensitivity to climate change</u>: High

Additional comments: The Clark's nutcracker is likely moderately sensitive to climate change.

References: Because whitebark pine cones do not split open when ripe, the species is heavily dependent on the caching habits of the Clark's nutcracker for seed dispersal (Hutchins and Lanner 1982 cited in Fryer 2002). Clark's nutcrackers break cones and bury the seeds in shallow caches (Tomback 1978, 1982 cited in Fryer 2002), where un-retrieved seeds may germinate into new trees (Hutchins and Lanner 1982, Lanner 1982, Lanner and Gilbert 1994 cited in Fryer 2002). However, when whitebark pines are impacted by blister rust or other disturbance that limits seed production, predation by Clark's nutcracker may leave very few seeds for regeneration (Tomback 2002 cited in Fryer 2002). Seed establishment is also aided by ectomycorrhizal fungi (Cripps and Antibus 2011).

---

9. Overall user ranking.

a. <u>Overall sensitivity of this species to climate change</u>: High
    i. Participant confidence: High

Additional comments: Overall sensitivity of this species to climate change is due to sensitivity to pine beetle, blister rust, temperature, and precipitation.

Adaptive Capacity

1. **Dispersal ability.**
    a. Maximum annual dispersal distance: 5-50 km (3.1-31 mi)
        i. Participant confidence: High
    b. Ability of species to disperse: High
        i. Participant confidence: High
    c. General types of barriers to dispersal include: Other – requires a disperser, geologic features (i.e., high elevations in the northern Sierra)
    d. Degree barriers affect dispersal for the species: High
        i. Participant confidence: High
    e. Possibility for individuals to seek out refugia: Yes, at the highest elevations.

Additional comments: Dispersal ability depends on dispersal agents, particularly the Clark's nutcracker.

---

2. **Plasticity.**
    a. Ability of species to modify physiology or behavior: Low
        i. Participant confidence: High
    b. Description of species' ability to modify physiology or behavior: Whitebark pine may demonstrate some variable seed morphology (i.e. wing vs. no-wing) if nutcracker or squirrel dispersal agents are absent.

Additional comments: Whitebark pine has long generation times.

References: Whitebark pines at high elevations also frequently experience near-hurricane-force winds (Biswell n.d. cited in Fryer 2002), and develop variations in trunk morphology (i.e. krummholz) that may provide protection against wind (Fites-Kaufman et al. 2007) and other disturbances.

---

3. **Evolutionary potential.**
    a. Ability of species to adapt evolutionarily: Moderate
        i. Participant confidence: Moderate
    b. Description of characteristics that allow species to adapt evolutionarily: Whitebark pine can evolve seeds with wings if dispersal agent is lost, but may lose some genetic diversity as a result. Genetic diversity currently exists because of long-range dispersal (i.e., via nutcracker).

Additional comments: Whitebark pine exhibits different morphologies at higher elevations (i.e., krummholtz for wind, which also protects against beetles).

References: Whitebark pine is slow-growing and long-lived (Arno and Hoff 1989). Stands older than 600 years have been found in Wyoming and Alberta (Luckman et al. 1984, Steele et al. 1983 cited in Fryer 2002), and the oldest recorded specimen was over 1200 years old (Perkins and Swetnam 1996 cited in Fryer 2002). Seed cones are first produced at 20 to 30 years; peak production is achieved at approximately 60 to 100 years, and lasts several hundred years (Lewis 1971, McCaughey and Tomback 2001 cited in Fryer 2002). Stand-wide and population-wide production of cones can be episodic. Clark's nutcracker seed-caching habits may result in tree clusters composed of related individuals. On a larger scale, long-distance dispersal by Clark' nutcracker may contribute to low inter-population diversity (Bruederle et al. 2001, Bruederle et al. 1998 cited in Fryer 2002).

---

4. **Intraspecific diversity/life history.**

a. Degree of diversity of species' life history strategies: Low
    i. Participant confidence: High
b. Description of diversity of life history strategies: Seed dispersal (e.g. wing vs. no-wing seeds)

Additional comments: Whitebark pines are 50-80 years old before they produce cones, and production increases after 100 years of age.

References: Differential responses to water deficit and maximum temperatures suggest that at least two genotypic groups of whitebark pines exist, with some trees better able to take advantage of warm conditions (Millar et al. 2012).

---

5. **Management potential.**
    a. Value level people ascribe to this species: Low-Moderate
        i. Participant confidence: High
    b. Specificity of rules governing management of the species: High
        i. Participant confidence: High
    c. Description of use conflicts: Ski resorts
    d. Potential for managing or alleviating climate impacts: A few areas do have management potential, for instance ski areas and USFS lands.

Additional comments: Currently a federal candidate species for ESA inclusion. Approximately 90% of whitebark pine range is in designated wilderness and protected areas.

References: Historically, whitebark pine was a major component of subalpine forests in the Sierra Nevada (Arno and Hoff 1989) and although the majority of whitebark pine range in California occurs within protected areas and designated wilderness, it has experienced significant declines in the western US and is now a candidate species for federal listing under the Endangered Species Act.

---

6. **Other adaptive capacity factors.**
    a. Additional factors affecting adaptive capacity: Ectomycorrhizal fungus, other animal dispersers (i.e. chipmunk, squirrel)
        i. Participant confidence: High
    b. Collective degree these factors affect the adaptive capacity of the species: Moderate

Additional comments: Whitebark pines are more diverse than bristlecone pines, but there still exists a lot of uncertainty, especially concerning responses to climatic change.

References: In seedlings, drought tolerance is conferred in part rapid growth of deep roots and thick, drought-resistant stems (Bruederle et al. 1998 cited in Fryer 2002). Moderate-thickness bark may support survival of mature trees during moderate- and low-intensity fires (Fryer 2002). In addition, whitebark pine forest growth patterns that form discontinuous canopies and sparse understories may further limit the spread and extent of fire (Botti 1979, Brown et al. 1994, and Steele et al. 1983 cited in Fryer 2002).

---

7. **Overall user ranking.**
    a. Overall adaptive capacity of the species: Low-Moderate
        i. Participant confidence: High

Additional comments: The whitebark pine is very sensitive to temperature, and dependent upon other species for seed dispersal and water uptake. It has long generations and not many life history strategies, but can exhibit other growth structures (e.g., krummholtz) in response to different environmental conditions.

Exposure

1. **Exposure factors[7].**
    a. Factors likely to be most relevant or important to consider for the species: Temperature, precipitation, climatic water deficit, wildfire, snowpack
        i. Participant confidence: High (temperature, precipitation, and snowpack); Moderate (climatic water deficit and wildfire)

2. **Exposure region.**
    a. Exposure by region: North – Moderate-High; Central – Moderate-High; South – High
        i. Participant confidence: High (all)

3. **Overall user ranking.**
    a. Overall exposure of the species to climate changes: High
        i. Participant confidence: High

Additional comments: Exposure factors considered especially important for whitebark pine include temperature and pine beetles.

References:
Vegetation shifts: In regions outside of the Sierra Nevada, models predict a decline in whitebark pine due to warming temperature and more frequent summer droughts (McCaughey 1994, Mattson and Reinhart 1997, McCaughey and Tomback 2001 cited in Fryer 2002).

Temperature: High elevation forests have seen pronounced increases in temperature over the past century (Dolanc et al. 2013b). 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[8] and PCM[9]) 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)

---

[7] Participants were asked to identify exposure factors (i.e., climate and climate-driven changes) most relevant or important to the species but were not asked to evaluate the degree to which the factor affects the species.
[8] 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.
[9] 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.

while others demonstrate more substantial changes (e.g. GFDL). In general, annual precipitation is projected to exhibit only modest changes by the end of the century (Hayhoe et al. 2004; Dettinger 2005; Maurer 2007; Cayan et al. 2008; 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 that falls as snow at the high elevations that characterize this part of the range (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 pattern 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).

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).

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 or >404 ha) 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). Historically, forest fires were relatively rare in alpine and subalpine vegetation, and did not play as strong a role in structuring these ecosystems as they did in lower elevation systems (Van de Water and Safford 2011; Safford and Van de Water 2013). However, with earlier snowmelt and warmer temperatures, models and current trends suggest that fire may become a more significant ecological disturbance in high elevation forests through the 21st century (Fites-Kaufman et al. 2007; Mallek et al. 2013), especially if climate warming leads to densification of bristlecone stands (Dolanc et al. 2013b).

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 cited in Strom and Fule 2007; McKenzie et al. 2004) 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).

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 species 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

Arno, S. F. and R. J. Hoff (1989). Silvics of Whitebark Pine (Pinus albicaulis), USDA Forest Service Intermountain Research Station. **General Technical Report INT-253**.

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.

Cripps, C. L. and R. K. Antibus (2011). Native Ectomycorrhizal Fungi of Limber and Whitebark Pine: Necessary for Forest Sustainability? The future of high-elevation, five-needle white pines in Western North America: Proceedings of the High Five Symposium, Missioula, MT, USDA Forest Service, Rocky Mountain Research Station.

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.

Dolanc, C. R., J. H. Thorne and H. D. Safford (2013). "Widespread shifts in the demographic structure of subalpine forests in the Sierra Nevada, California, 1934 to 2007." Global Ecology and Biogeography **22**(3): 264-276.

Dolanc, C. R., R. D. Westfall, H. D. Safford, J. H. Thorne and M. W. Schwartz (2013). "Growth–climate relationships for six subalpine tree species in a Mediterranean climate." Canadian Journal of Forest Research **43**(12): 1114-1126.

Fites-Kaufman, J. A., P. Rundel, N. Stephenson and D. A. Weixelman (2007). Montane and Subalpine Vegetation of the Sierra Nevada and Cascade Ranges. Terrestrial Vegetation of California. Berkeley, University of California Press**:** 456-501.

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.

Fryer, J. L. (2002). Pinus albicaulis. Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/plants/tree/pinalb/all.html.

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.

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.

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.

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.

Mallek, C. R., H. D. Safford, J. H. Viers and J. Miller (2013). "Modern departures in fire severity and area vary by forest type, Sierra Nevada and southern Cascades, California, USA." Ecosphere **4**(12): 1-28.

Maloney, P. E. (2011). "Incidence and distribution of white pine blister rust in the high-elevation forests of California." Forest Pathology **41**(4): 308-316.

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.

Millar, C. I., R. D. Westfall and D. L. Delaney (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.

Millar, C. I., R. D. Westfall and D. L. Delany (2010). Mortality in Subalpine Forests of the Sierra Nevada, California, USA: Differential Response of Pines (Pinus albicaulis and P. flexilis) to Climate Variability. AGU Fall Meeting.

Millar, C. I., R. D. Westfall, D. L. Delany, M. J. Bokach, A. L. Flint and L. E. Flint (2012). "Forest mortality in high-elevation whitebark pine (Pinus albicaulis) forests of eastern California, USA; influence of environmental context, bark beetles, climatic water deficit, and warming." Canadian Journal of Forest Research **42**(4): 749-765.

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.

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).

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. D., J. T. Stevens, K. Merriam, M. D. Meyer and A. M. Latimer (2012). "Fuel treatment effectiveness in California yellow pine and mixed conifer forests." Forest Ecology and Management **274**: 17-28.

Safford, H. D. and K. M. Van de Water (2013). Using Fire Return Interval Departure (FRID) analysis to map spatial and temporal changes in fire frequency on National Forest lands in California. Albany, CA, USDA Forest Service, Pacific Southwest Research Station. **General Technical Report PSW-GTR-247**.

Scholl, A. E. and A. H. Taylor (2010). "Fire regimes, forest change, and self-organization in an old-frowth mixed-conifer forest, Yosemite National Park, USA." Ecological Applications **20**(2): 362-380.

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 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**.

Tomback, D. F. and P. Achuff (2010). "Blister rust and western forest biodiversity: ecology, values and outlook for white pines." Forest Pathology **40**(3-4): 186-225.

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.

EcoAdapt™

Meeting the challenges of climate change

EcoAdapt, founded by a team of some of the earliest adaptation thinkers and practitioners in the field, has one goal - creating a robust future in the face of climate change. We bring together diverse players to reshape planning and management in response to rapid climate change.

P.O. Box 11195
Bainbridge Island, WA 98110

EcoAdapt.org
+1 (206) 201 3834