Chapter 2: Climate Change Effects in the Sierra Nevada

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Climate Overview for the Sierra Nevada

The Sierra Nevada region is characterized by high topographical and climatological diversity (Dettinger et al. 2018), extending 400 mi north to south and 70 mi east to west. Elevations are higher in the southern end of the range, with Mount Whitney (14,505 ft) being the highest peak in the contiguous United States; peaks in the northern part of the range are generally less than 8,800 ft (Minnich and Padgett 2003).

The western portion of the Sierra Nevada region is characterized by a Mediterranean climate, with cool, wet winters and warm, dry summers. The western portion of the Sierra Nevada receives moisture and warm air from prevailing westerly winds off the North Pacific Ocean (Dettinger et al. 2018). As air moves upward over the mountain range, air cools, and moisture condenses into clouds and precipitation. Thus, the western, mountainous portions of the Sierra Nevada receive more precipitation than the eastern portion (fig. 2.1); elevations between 5,000 and 6,000 ft on the west slope are some of the wettest in the region (Dettinger et al. 2018).

The eastern portion of the Sierra Nevada region lies in a rain shadow and thus receives less precipitation (fig. 2.1). The eastern portion of the range is also more heavily influenced by Great Basin climate, with colder winters and more rainfall in the summer (Dettinger et al. 2018). Temperatures are generally cooler and more precipitation falls as snow in the southern portion of the Sierra Nevada than the central and northern portions of the range because of higher elevations (fig. 2.1). However, average annual precipitation decreases gradually moving southward because of the position of the jetstream in northern California and the Pacific Northwest during winter (Minnich and Padgett 2003).

The Sierra Nevada region, and California in general, are characterized by high interannual variation in precipitation. Historically, annual precipitation in the Sierra Nevada has varied between 50 and 200 percent of average, whereas most of the rest of the United States varies between 10 to 20 percent of average (Dettinger et al. 2011). Although the Pacific Ocean has a moderating effect on temperature in the western part of California, other ocean-atmosphere cycles, such as the El Niño Southern Oscillation, contribute to interannual climatic variability in the state and the Sierra Nevada region (Dettinger et al. 2018).

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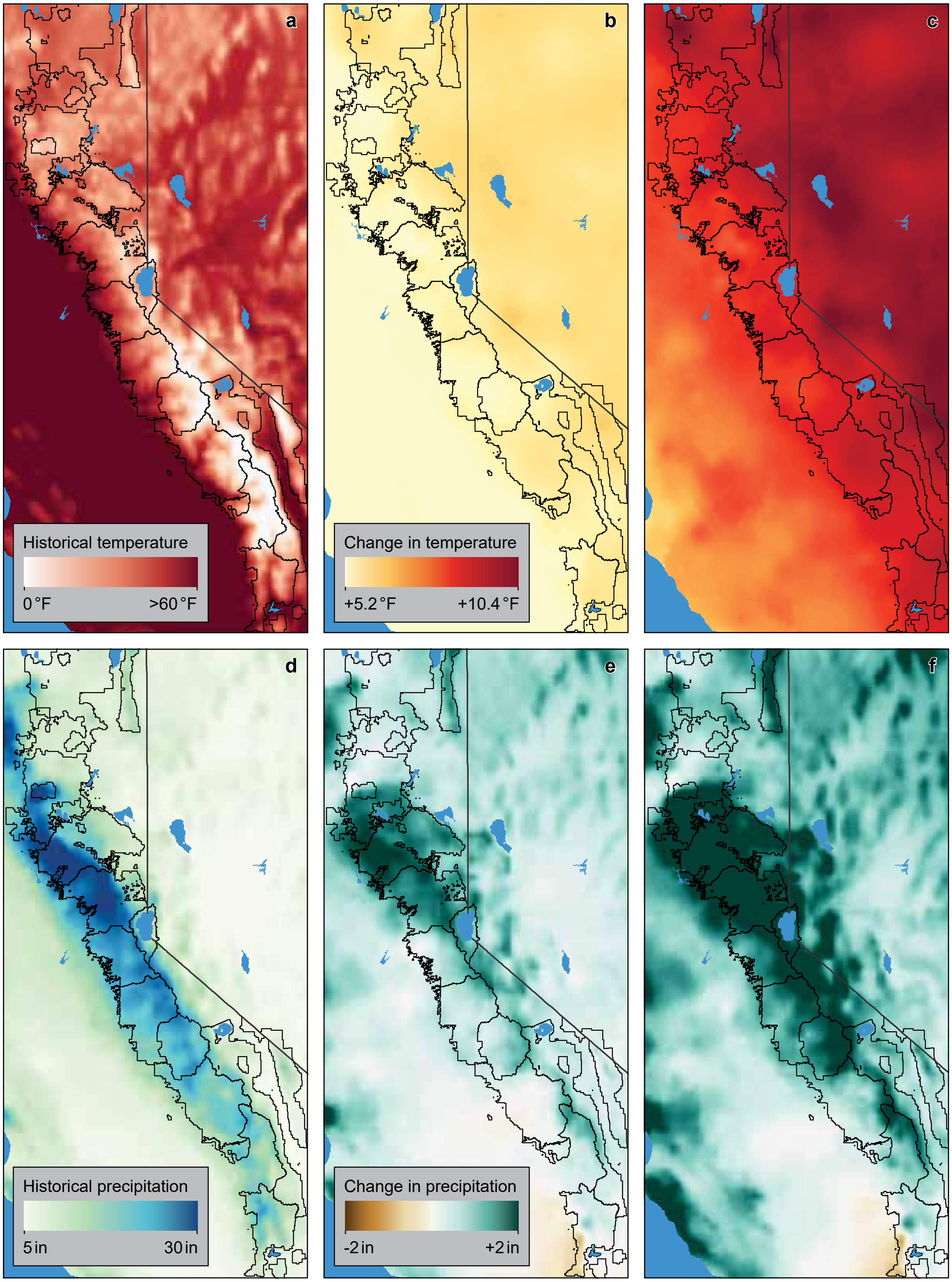

Figure 2.1—Historical (1961–1990) average annual temperature (a) and precipitation (d); and average changes in temperature (b and c) and precipitation (e and f) by 2070–2099, as projected by 10 global climate models under moderate greenhouse gas emissions (Representative Concentration Pathway [RCP] 4.5; b and e) and high greenhouse-gas emissions (RCP 8.5; c and f). Sierra Nevada National Forest boundaries are shown in black. (Data courtesy of M. Dettinger. Adapted from Dettinger et al. 2018. Figure by R. Norheim)

Observed and Projected Climate in the Sierra Nevada

The Sierra Nevada is already experiencing the effects of human-caused climate change. Temperatures have increased in recent decades (Safford et al. 2012, Vose et al. 2017). Between 1901 and 2016, average annual temperatures for the Southwest United States (including California) increased by 1.6 °F (Vose et al. 2017). Temperatures during the decade from 2001 to 2010 were the highest in the 110-year instrumental record for the same region (Hoerling et al. 2013).

Increased winter temperatures have resulted in more precipitation falling as rain rather than snow (Knowles et al. 2006) and reduced snowpack in many parts of the Sierra Nevada; most snow-course sites had declines in April 1 snow-water equivalent (a measure of snowpack) between 1955 and 2016 (Mote et al. 2018). Reduced snowpack and earlier snowmelt have led to earlier timing of streamflow in the Sierra Nevada (Stewart et al. 2005). Increased spring and summer temperatures have also been associated with increased wildfire area burned (Littell et al. 2009, Westerling 2016, Westerling et al. 2006) and incidence of large fires (Dennison et al. 2014). These effects are expected to continue and become more pronounced in coming decades (Dettinger et al. 2018)

A chapter on the Sierra Nevada in the fourth California climate assessment (Dettinger et al. 2018) provides climate projections for the region from the latest global climate model runs. These future climate projections (from a set of 10 global climate models) suggest that temperatures in the Sierra Nevada will, on average, increase by 6 to 10 °F by the end of the 21st century, depending on the concentration of greenhouse gases in the atmosphere (fig. 2.1).[2]

Temperature increases are projected to be lower under RCP 4.5, which assumes that emissions peak by mid-century and stabilize at low levels by about 2080. Projected temperature increases are higher under RCP 8.5, which assumes that emissions continue to rise throughout the 21st century. Under RCP 8.5, projected average annual temperature increases are 9 °F in the northern Sierra Nevada (including the Plumas, Tahoe, and Eldorado National Forests [NFs]), 9.2 °F in the southern Sierra Nevada (including the Stanislaus, Sierra, and Sequoia NFs), and 9.8 °F in the northeast (Modoc and Lassen NFs) and southeast (Inyo NF) portions of the range (figs. 2.1b-c). Under RCP 4.5, projected warming is 3 to 4 °F less (Dettinger et al. 2018). Extreme high temperatures are projected to increase even more than average temperatures (Hayhoe et al. 2018).

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[2] The Representative Concentration Pathways (RCPs) used in Intergovernmental Panel on Climate Change reports represent scenarios about future concentrations of greenhouse gases in the atmosphere as a result of human activities.

Projections for precipitation are more uncertain than those for temperature. Future precipitation is expected to change less than temperature, by about -5 percent to +10 percent depending on location in the Sierra Nevada (fig. 2.1e-f). Precipitation may increase somewhat in winter and decrease slightly or stay about the same in other seasons (Dettinger et al. 2018, Hayhoe et al. 2018). However, these changes are likely to be small compared to the wide interannual variability in precipitation in the region (Dettinger et al. 2018).

Although the total amount of precipitation may not change considerably in the future, precipitation extremes are projected to increase. The amount of precipitation from the largest storms, including atmospheric rivers, is expected to increase by 5 to 30 percent compared to a historical period, depending on future greenhouse gas emissions (Dettinger et al. 2018). The number of dry days between storms is also expected to increase (Polade et al. 2017). Higher temperatures (and longer time periods between rain events) will likely increase drought stress in forests because hotter temperatures (and hotter droughts) increase water demand from vegetation far beyond what any small increase in precipitation might provide.

Climatic changes are likely to vary across the Sierra Nevada landscape. Increases in temperature are expected to be higher at higher elevations (+9 °F at 3,000 ft compared to +9.5 °F at 10,000 ft) (Dettinger et al. 2018). Precipitation may increase more in the northern portion of the Sierra Nevada (fig. 2.1f). Topographic influences such as cold air drainage will also result in spatial variability in temperature and precipitation changes (Morelli et al. 2011).

Climate Change Effects on Hydrology

The Sierra Nevada is a critical source of water resources to otherwise water-limited ecosystems and downstream communities. As a result of the Mediterranean climate, approximately 80 percent of total annual precipitation falls during the cool winter months, typically followed by a warm, dry summer (Belmecheri et al. 2015). Precipitation events are driven by orographic uplift, where moisture held in air masses delivered by the mid-latitude jetstream precipitates as air is forced into higher and colder elevations. Because of these orographic effects, higher elevations typically have the highest precipitation and snow accumulation rates. At mid to high elevations, precipitation regimes are largely snow dominated.

Across the Sierra Nevada, annual snowpack accumulation is highly variable and a function of topography, elevation, atmospheric circulation patterns, temperature, incoming precipitation, and vegetation. The snow accumulation season is also shorter than in other mountain ranges in the Western United States, with a majority of precipitation events occurring from December through March. A few large snow events often comprise the majority of the total annual snowpack (Huning and

Margulis 2017). Across the region, the total average amount of annual precipitation stored in mountain snowpacks is approximately two-thirds the volume of water capacity of California's human-made reservoir network (Dettinger et al. 2018). Historically, this water has been slowly released as snowmelt throughout the spring months and into summer.

Although precipitation patterns in the Sierra Nevada exhibit large interannual variability, and will be uncertain in the future, the effects of climate change are already having measurable impacts on hydrological processes and water resources. Low precipitation coupled with above-average temperatures have led to snowpack deficits and severe drought in recent years. Warmer temperatures reduce snow levels by both decreasing the fraction of precipitation falling as snow relative to rain and increasing melt rates, thus reducing snow residence time.

During the 2012–2017 drought, higher temperatures attributed to climate change exacerbated drought conditions and reduced snowpack levels by an additional 25 percent, with declines greater than 40 percent in the most vulnerable elevations (Berg and Hall 2017). The frequency and intensity of these recent droughts are expected to increase through the 21st century, likely resulting in snowpack reductions of 60 to 85 percent from historical levels, depending on future greenhouse gas emissions.

Although patterns and processes of snow accumulation and melt will likely be altered with climate change, much of the Sierra Nevada is characterized by steep environmental gradients and complex terrain. Owing to this heterogeneity, the effects of climate change on snowpack and hydrologic processes may be highly variable across the landscape. However, snowpack at elevations of 5,000 to 8,000 ft are the most vulnerable to warming temperatures, and these mid-elevations comprise over 60 percent of the current snow-dominated extent of the Sierra Nevada.

Climate-related shifts in patterns and timing of snow accumulation and melt will likely have cascading effects on streamflow from catchment to landscape scales. Coupled with declining snowpacks, shifts in streamflow timing have been detected across the Western United States, with rivers in the Sierra Nevada exhibiting some of the highest sensitivity to temperature increases. Over the past half-century in the Sierra Nevada, snowmelt-derived peak streamflows have occurred 10 to 30 days earlier in the spring (Stewart et al. 2005). As precipitation regimes transition from snow dominated to rain dominated, winter and spring streamflows may become flashier, as rain immediately runs off, and rain-on-snow events can trigger rapid snowmelt. Earlier peak streamflows are expected to continue into the 21st century, with advances occurring 80 days earlier than historical averages under a high emission scenario (Schwartz et al. 2017).

Shifts in winter and spring streamflows can also affect summer low flows. Compared to other river systems across the Western United States, streams in the Sierra Nevada show the strongest negative trends in fractional flows during summer months (Stewart et al. 2005). Future declines in summer flows may place increasing pressure on aquatic ecosystems and water resource infrastructure as water becomes increasingly limited during severe drought and periods of peak demand.

The distribution and productivity of forest ecosystems across the Sierra Nevada are largely shaped by water availability. Hydrologic shifts will likely affect vegetation through lower soil moisture and higher evaporative demand. Altered distribution and amount of soil moisture available to plants, along with increasingly dry atmospheric conditions, may lead to increased vulnerability of drought-sensitive plant species and ecosystems. In the Sierra Nevada, peak soil moisture is sensitive to the last day of snow presence, suggesting that future declines in precipitation falling as snow and rapid melt rates may lead to higher soil moisture deficit later in the summer (Harpold and Molotch 2015).

Higher temperatures will also likely lead to drier atmospheric conditions. For example, climatic water deficit (Lutz et al. 2010) and vapor pressure deficit (Ficklin and Novick 2017), both metrics describing the drying capacity of the atmosphere, are projected to increase with warming air temperatures. Increased frequency and extent of drought in the future would reduce soil moisture availability for plants, reducing tree vigor, and, in some cases, causing tree mortality.

Climate Change Effects on Fire and Vegetation

The climatic and topographic diversity of the Sierra Nevada and proximity to other bioregions contribute to its diverse vegetation assemblages (Minnich 2007). Approximately half of California’s 7,000 plant species occur in the Sierra Nevada, and 400 occur only in the Sierra Nevada (USDA FS 2014). On the west slope of the Sierra Nevada, vegetation ranges from chaparral and foothill woodlands, to mixed-conifer forests at mid elevations, to subalpine forests at high elevations. Alpine vegetation types are found above treeline. Descending the east side of the range, there are narrow belts of subalpine and pine-dominated forests, with pinyon-juniper woodlands and desert scrub vegetation types at lower elevations (Minnich and Padgett 2003). The Modoc Plateau and the northeast part of the Sierra Nevada region have scattered conifer forests and large areas of singleleaf pinyon pine (*Pinus monophylla* Torr. & Frém.), western juniper (*Juniperus occidentalis* Hook.), and big sagebrush (*Artemisia tridentate* Nutt.). The White Mountains and Inyo Mountains (Inyo NF) are high-elevation desert landscapes with little vegetation cover, but with iconic tree species such as Great Basin bristlecone pine (*P. longaeva* D.K. Bailey) and foxtail pine (*P. balfouriana* Balf.).

Climate change is likely to alter the species composition and structure of vegetation in the Sierra Nevada. Altered disturbance regimes (e.g., drought, insects, wildfire) are likely to be the major catalysts of vegetation change (Safford et al. 2012). The 2012–2017 drought, insect damage, and associated forest mortality in the Sierra Nevada (Fettig et al. 2019) illustrate how extreme climatic events can affect ecosystems in the region.

Wildfire, which is directly affected by climate, is a dominant ecological process in the Sierra Nevada. Modern climate and fire records indicate that over the past century in the Western United States, warm and dry conditions in any given year (primarily in summer, but also in winter and spring) generally have led to larger fires and more area burned (Abatzoglou and Kolden 2013, Dennison et al. 2014, Kitzberger et al. 2017, Littell et al. 2009, McKenzie et al. 2004, Stavros et al. 2014, Westerling 2016, Westerling et al. 2006). Warmer spring and summer conditions led to increased evapotranspiration, lower summer soil and fuel moisture, and longer fire seasons (Westerling 2016, Westerling et al. 2006). Dry fuels and longer fire seasons are associated with higher area burned (Gedalof et al. 2005), although summer precipitation is an important modifier of fire activity (Holden et al. 2018).

A warming climate in future decades will have profound effects on fire frequency and extent in the Sierra Nevada. Simulations by Lenihan et al. (2003, 2008) indicated a 5 to 8 percent increase in annual area burned in California, depending on future climate. Projections by Westerling and Bryant (2008) suggested risk of large fires will increase by 12 to 53 percent by the end of the century across California, depending on climate scenario. For the Sierra Nevada, Liang et al. (2017) projected increases in fire area burned per decade of 393,000 to 457,000 ac. They also projected increases in fire size and decreases in fire rotation. Recent projections by Westerling (2018) indicate that annual average area burned in parts of the Sierra Nevada may double or quadruple by end of century (comparing 2070–2099 to 1961–1990) under RCP 8.5. Although these projections vary (because of differences in model types and assumptions), it is clear that increased fire area burned is likely in a warmer future in the Sierra Nevada. Fire severity may also increase, depending on how climate alters disturbance regimes and fuels (Safford et al. 2012).

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Increases in area burned and moisture deficits are likely to shift vegetation composition to more fire- and drought-tolerant species over decades to centuries. These changes are likely to occur more quickly in areas where disturbance frequency is higher at low to mid elevations. Using the LANDIS-II landscape model, Liang et al. (2017) projected increased recruitment of drought-tolerant species (e.g., oak [*Quercus* spp.], gray pine [*P. sabiniana* Douglas ex Douglas], ponderosa pine, pinyon pine, and Jeffrey pine [*P. jeffreyi* Balf.]) in Sierra Nevada forests in a warming climate, particularly at mid-elevations, because of increased wildfire and moisture limitations; less drought-tolerant species (e.g., white fir [*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.], Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], and Shasta red fir [*A. magnifica* A. Murray]) had much lower recruitment. However, if fire sizes increase substantially in the future, recruitment failures of drought-tolerant species may also occur

In lower elevation mixed-conifer forest, woodland species may increase in abundance. In general, broadleaf trees, such as oaks, may increase in abundance with loss of winter frost and increases in nighttime temperatures (Lenihan et al. 2003, 2008). Increased area burned and drought severity will likely favor shrubs in mid- and low-elevation forests (Airey Lavaux et al. 2016, Minor et al. 2017). Grasslands may also expand in area, particularly in a hotter and drier climate with frequent fire (Lenihan et al. 2003, 2008).

Increased area burned is likely to lead to increased area burned at high severity (Miller and Safford 2012), decreasing the fraction of old-growth forest patches and connectivity of these patches across the landscape (McKenzie et al. 2004). Increasing summer drought stress will decrease growth for many species in mid- to low-elevation forests (Restaino et al. 2016), and increase vulnerability to insects and disease, likely causing tree mortality in some locations (Allen et al. 2015, Fettig et al. 2019). Second-growth forests with high stem density and surface fuel loadings may be particularly vulnerable to drought, fire, and insect outbreaks in the future.

Decreased snowpack and a longer growing season (Kershner 2014; Lenihan et al. 2003, 2008) may reduce habitat for subalpine and alpine vegetation types in some locations in the Sierra Nevada, as conditions become more suitable for lower elevation conifer species. However, warmer temperatures, earlier snowmelt, and longer growing seasons may increase subalpine conifer growth (Graumlich and Brubaker 1986, Peterson and Peterson 2001), and conifer encroachment in meadows will likely increase (Millar et al. 2004). Drought and fire may become more common disturbances (Fites-Kaufman et al. 2007), although north aspects are likely to remain cooler, retain more snow, and provide refugia for high-elevation plant and animal species (Kershner 2014).

Climate Change Effects on Fish and Wildlife

Altered climate, disturbance regimes, and vegetation composition and structure will affect animal species in the Sierra Nevada. Increasing temperatures and changing precipitation will have direct physiological effects on some species. Other species may be affected indirectly through altered phenology (timing of life history) relative to forage plants and invertebrate prey; shifts in geographic ranges and density and ranges of competitor, forage, prey, and symbiotic species (and subsequent changes in biotic interactions); and effects from other stressors such as fire, insects, and disease. Related changes in habitat characteristics and quality will affect animal species viability. These effects will interact with existing stressors, leading to complex responses of wildlife populations to changing climate.

Distribution and abundance of birds, mammals, and amphibians are all expected to shift with changes in climate in the Sierra Nevada (Lawler et al. 2009a, 2009b; Stahlberg et al. 2009). Some species ranges may move to higher elevations as temperature increases (Forister et al. 2010, Moritz et al. 2008, Rowe et al. 2015). However, range shifts will depend on factors such as altered distribution and abundance of plant species, specific habitat conditions, predator-prey relationships, and species physiological tolerances (Inkley et al. 2004). The ability of animal species to disperse or migrate will depend on the availability of migration corridors and suitable habitats, and the concurrent movement of forage, prey, and cover.

Species sensitivity to climate change will vary. Increased variability and more extreme conditions with climate change will likely favor species adapted to frequent disturbance and some invasive species (Friggens et al. 2018). It may be more difficult for endemic and specialist species with narrow habitat requirements or dependencies on specific forage species to find suitable habitat under changing climate. For example, old-growth specialists such as the California spotted owl (*Strix occidentalis occidentalis* Xántus de Vésey) and Pacific fisher (*Pekania pennanti* Erxleben) are likely to be negatively affected by changes in fire regimes and reduced connectivity of late-successional forests (Scheller et al. 2011). In contrast, generalist species with high climatic tolerance, broad habitat and forage requirements, and high dispersal ability may increase in abundance (Pounds et al. 2005).

Aquatic species in the Sierra Nevada will be affected by warmer stream temperatures and changes in the quantity and timing of streamflow. Anadromous salmonid species in California are the southernmost native populations of their species, many of which are already considered threatened or endangered (Katz et al. 2013). Increases in summer water temperatures will likely result in stressful or lethal conditions for coldwater-adapted fish species in many streams in the Sierra Nevada, particularly in the northern and central portion of the range (owing to lower elevations) (Null et al. 2013). Thus, climate change will likely interact with other existing stressors (e.g., degraded habitat, hydropower, nonnative species) to increase risk of salmonid extinction (Katz et al. 2013, Null et al. 2013). Species restricted to limited areas, such as Kern golden trout (*Oncorhynchus mykiss whitei* Evermann), are particularly vulnerable (Katz et al. 2013, Moyle et al. 2011).

Amphibian species will also be affected by warming temperatures and altered hydrology. There are many endemic amphibian species in the Sierra Nevada, many of which have narrow ranges and are sensitive to disturbance and temperature increases (Kershner 2014). For example, mountain yellow-legged frogs (*Rana muscosa* Camp) occur in limited locations, and drying in summer would have detrimental effects (USDA FS 2014). Warmer temperatures are also likely to make frogs more vulnerable to some diseases (Pounds et al. 2006).

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