3.1 Terrestrial Ecosystems and Biodiversity

Ecosystems and their constituent species play key roles in shaping the structure and function of the Sierra Nevada region. The composition and structure of these ecosystems range from productive conifer forests along the western slopes of the Sierra Nevada and graceful oak woodlands in the western foothills to the mixed chaparral on the drier Eastside subregion (Fig. 1.1a) and the ecologically and hydrologically important montane meadows. Species richness and endemism in the Sierra Nevada rank among the highest in the world for temperate forests (Murphy et al. 2004). In this section, we focus on three ecosystem types: forests, oak woodlands, and meadows, as well as the wildlife species that inhabit these ecosystems. Separating ecosystems topics from biodiversity is fraught with overlaps and linkages, but by and large this section focuses on forest, oak woodland, and meadow habitat disturbances (including wildfire) and carbon storage under the heading "Ecosystems," and species populations and ecological communities under the heading "Biodiversity."

3.1.1 CLIMATE EFFECTS, TRENDS AND PROJECTIONS IN ECOSYSTEMS

3.1.1.1 Focal Ecosystems

Climate is a major driver of ecosystem composition, structure, and dynamics in forests, oak woodlands, and meadows.

Forests are a defining feature of the Sierra Nevada region. Not only are they most abundant vegetation (FRAP Vegetation 2015), but they also dominate ecosystem function given their productivity (Gonzalez et al. 2015) and their role as foundational species (Ellison et al. 2005). Regional climate, soil resources, available biota, and disturbances—like wildfire, human uses, and insects—influence the composition and structure of Sierra Nevada forests (Chapin et al. 1996, Safford and Stevens 2017). Humans are shifting the effects of these influences by a century-long policy of fire suppression (see FIRE BOX) and, more recently, a warming climate (Wang et al. 2017).

Woodlands in the Sierra Nevada grow in the foothills in the form of oak woodlands and as a component of montane forests. California oak woodlands boast a high diversity of understory plant, vertebrate, and invertebrate species. Oaks within oak woodlands and montane forests have varying degrees of adaptation to fire. Other disturbances consequential to oak woodlands include livestock grazing and land conversion. Livestock grazing can change fire behavior by reducing fuel loads, altering understory plant communities, and reducing seedling and sapling recruitment of oak species (Davis et al. 2011). Conversion of oak woodlands for agricultural and urban/residential uses serves to impact oak woodlands through direct removal and fragmentation (Davis et al. 2016).

Sierra Nevada montane meadows are highly biodiverse areas relative to surrounding forests and provide important habitat, hydrological, and carbon storage functions. Meadows are, in part, characterized by their seasonally or perennially saturated soils that support a diverse assemblage of grasses, forbs, and shrubs, which in turn supplies forage for domestic and native herbivores and habitat for amphibians, aquatic invertebrates, and mammals (Patton and Judd 1970, van Riper III and van Wagtendonk 2006, Wang 2012). Mountain meadows have a relatively outsized contribution to the hydrology of the surrounding landscape by slowing the release of snow meltwater downstream (Hammersmark et al. 2008). This reduces flood risk and is ecologically significant to biota dependent on these flows. Intact wet meadows are important groundwater-dependent ecosystems.

3.1.1.2 Trends and projections

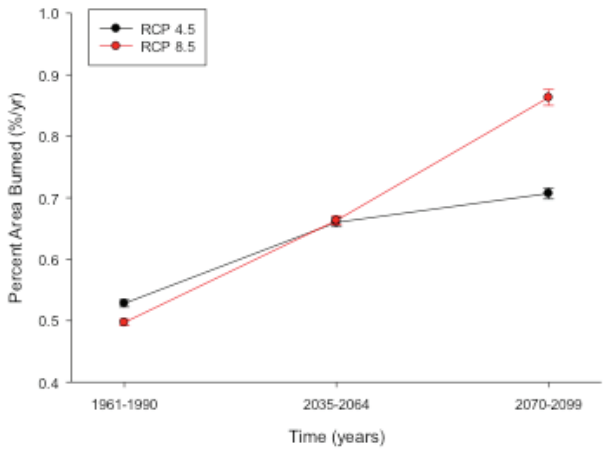
Even optimistic projections of warming lead to more wildfire, more drought stress, and lower carbon storage.

Climate is a fundamental determinant of ecosystem structure and function. Indeed, forests only occur in regions where the climate provides supplies of energy and water that are sufficient to support the growth of trees (Stephenson 1998). In drier and/or colder climates, shrubs and herbaceous plants dominate. In addition, there is a strong link between climate and fire (Moritz et al. 2012). Thus, a changing climate poses multiple threats to Sierra Nevada region ecosystems. For example, Liang et al. (2017) modelled the interactive effects of climate warming and wildfire on forest composition and carbon storage for the Sierra Nevada. Their end-of-century projections include declines in forest productivity, reductions in species richness, and shifts in forest composition. The observed increase in tree mortality in the Westside South subregion provides a contemporary, empirical example of climate change impacts. Mortality rates between 1983 and 2004 nearly doubled while water deficit increased during the same interval (van Mantgem and Stephenson 2007). More dramatically, the epic drought of 2012-2016 (Swain 2015, USGS 2018) triggered massive tree mortality in the Sierra Nevada (Young et al. 2017). A warming climate can also increase the frequency and severity of wildfires (Westerling et al. 2006, Restaino and Safford in press).

WILDFIRE

In the Sierra Nevada, currently projected changes in climate are associated with large increases in the area burned by wildfire (Fig. 3.1.1) and in the frequency of large fires with large fires defined as burning more 24,700 acres (Westerling et al. in review). Large fires are a particular concern because they can lead to conditions under which forest recovery is delayed or permanently shifted to shrub dominated landscapes (Stephens et al. 2014, Welch et al. 2016, Shive et al. 2018). The predicted changes exacerbate trends in the fire regime already evident in the Sierra Nevada (Box 1; Miller et al. 2009, Mallek et al. 2013, Steel et al. 2015). Regardless of the emissions pathway, wildfire is expected to increase throughout the century. However, the extent is particularly worrisome under the RCP 8.5 scenario. For example, in Madera County under RCP 4.5, area burned per year is estimated to be 4,438 acres by the end of the century (2070-2099) — a 70% increase over observed rates between 1961 and 1990. Under RCP 8.5, almost 9,000 acres per year will burn, representing a 241% increase (Cal Adapt 2018). The frequency of large fires follows these same trends.

FIGURE 3.1.1



Ensemble summaries of projected change in wildfire for the Sierra Nevada region, in percent of area burned per year. Results represent means and standard errors per grid cell (8,135 ac) from simulations based on four climate models, three land-use scenarios, and ten different potential vegetation responses to climate change. Responses to two different greenhouse-gas emission pathways are summarized over three time periods. From Westerling et al.

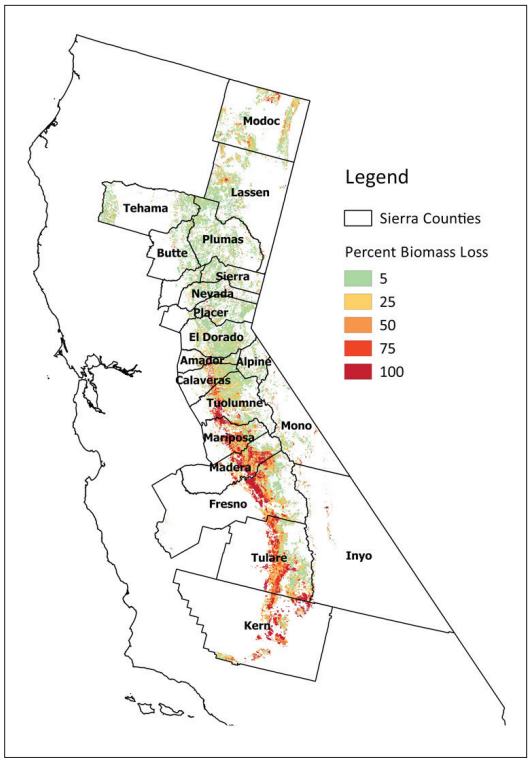
EXTREME EVENTS AND CLIMATE VARIABILITY

An important aspect of the projected climate is the increased potential for extreme events like storms and droughts. A future with a greater likelihood of multi-year or even multi-decade droughts (Ault et al. 2014) poses serious risks to the health of Sierra Nevada ecosystems. For example, the recent 2012-2016 drought was unprecedented because the lack of precipitation coincided with four, unusually warm years (Asner et al. 2016). The combination inflicted widespread water stress in Sierra Nevada forests (Young et al. 2017), which in turn weakened trees particularly in the southern Sierra Nevada.

Weakened trees can facilitate bark beetle outbreaks (Preisler et al. 2017) with devastating results. As of 2017, drought-related mortality has killed almost 110 million trees in the Sierra Nevada region (Sierra Nevada Conservancy 2018). Mortality related to drought varied by county (Fig 3.1.2). The southern end of the range experienced the highest mortality. Specifically, Lara et al. (In review) estimated a 26.5% loss of live trees in the South Range between 2012 and 2017 compared to 1.9% in the North Range. Presumably this variability was due to the higher drought stress experienced in the South Range (Young et al. 2017). The death of live trees directly translated to declines in live tree biomass, which in turn reduced the amount of carbon stored in these forests.

The increase in interannual variability in precipitation that has been both projected and documented for the Sierra Nevada (Safford et al. 2012b) also brings the potential for occasional years of extremely high rain and snowfall. Water year 2016-2017 was an excellent example, when four years of extreme drought (2012-2016) were followed by the wettest year on record. Record snowpack and spring-summer streamflow led to major flooding events and a wave of destructive snow avalanches, both of which disturbed large areas of forest (Safford, pers. obs.). Very high soil and fuel moistures through much of the summer also depressed wildfire activity at higher elevations, while wildfire risk at lower elevations was increased due to heavy grasses that cured in the very hot 2017 summer.

FIGURE 3.1.2



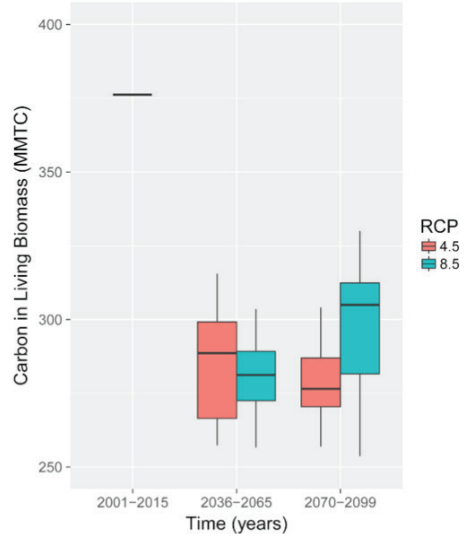
Projections of tree biomass loss as a result of the 2012-2016 drought. Estimates current to 2017 forest health surveys. Lara et al. (In review).

CARBON STORAGE

The forest ecosystems of California store almost 2 billion metric tons of carbon (Christensen et al. 2017), and the Sierra Nevada region accounts for more than half of this storage. Between 2001-2005 and 2011-2015, live trees in the region removed on average 9.5 million metric tons (MMT) of carbon dioxide equivalents per year from the atmosphere (Christensen et al. 2017). However, projected changes in climate imperil the forest carbon balance. During the 21st century, increases in wildfire hazard, drought frequency, and forest vulnerability will represent threats to the survival and growth of trees. Simulations based on the Land Use and Carbon Scenario

Simulator, a model that incorporates both projected disturbances (i.e., wildfire) and land-use change (i.e., development), indicate that, by mid-century, the Sierra Nevada will lose more than 25% of the carbon stored in living biomass (Fig. 3.1.3). Carbon storage is projected to stabilize at this reduced level and no losses are projected later in the century. Liang et al. (2017) also simulated 21st century carbon trends for the Sierra Nevada under climate change using a different, spatially explicit landscape succession model. While the details vary, this study also projected an end-of-century decline in the carbon balance.

FIGURE 3.1.3



Ensemble summaries of projected change in carbon stored in living biomass for the Sierra Nevada region, in million metric tons of carbon (MMTC). Results represent the range of values simulated under climate projections from four climate models and four land-use scenarios responding to two different greenhouse-gas futures. The boxes represent the 25th and 75th quartiles with the median denoted by the black horizontal lines. Note that results for the current period (horizontal line) have no uncertainty. From Sleeter et al. In review.

BIOGEOGRAPHIC SHIFTS

Even in the absence of droughts and severe wildfire, climate change can disrupt plant communities. Climate change can influence species abundance in myriad ways, from direct physiological effects on individuals, to indirect effects on species interactions, to changes in habitat quality (Rubidge et al. 2011, Jones et al. 2016a). For example, climate plays a pre-eminent role in determining the range of temperate tree species (Simova et al. 2015). Tree growth, survival, and recruitment are intrinsically tied to patterns in precipitation and air temperature. Thus, as the climate shifts, habitat conditions can shift and change as well (Millar et al. 2004). Species near the edge of their range are particularly vulnerable since even small climatic changes can limit their ability to persist (Thorne et al. 2017).

3.1.2 CLIMATE EFFECTS, TRENDS, AND PROJECTIONS FOR BIODIVERSITY

3.1.2.1 Physiology

Climate change can directly impact physiological processes in sensitive species.

Direct physiological effects of climate change may initially result in reductions in species reproduction and survival, eventually manifesting in population declines and/or species range shifts for cool adapted or thermally sensitive species. While evidence of direct physiological effects of climate change on wildlife are difficult to detect, impacts have been hypothesized for a variety of species in the Sierra Nevada, particularly old growth specialists of concern like spotted owls (*Strix occidentalis*) and Pacific fishers (*Pekania pennanti*). In some parts of the spotted owl's range, drought and high temperatures during the previous summer have been linked to lower survival and recruitment the following year (Franklin et al. 2000, Glenn et al. 2011, Jones et al. 2016a) and hot, dry summers likely negatively affect spotted owl populations (Glenn et al. 2010, Peery et al. 2012). Jones et al. (2016a) note that an increase in summer temperatures from 1993 to 2012 occurred concurrently with declines in spotted owl occupancy, predicting further declines in spotted owl populations under all future climate scenarios. While dense forest microclimates may partially mitigate large-scale climate changes, they are unlikely to eliminate all future impacts. Direct physiological effects of climate change have also been hypothesized for species associated with

other microclimates, like American pika (*Ochotona princeps*). Warm summers and cold, dry winters are thermally unfavorable to pikas; however local temperature regimes in rocky settings with which they are associated may buffer against changing climates (Millar et al. 2018).

3.1.2.2 Shifting species ranges

Observed changes in distributions of mammals, butterflies, and birds demonstrate that future range shifts are likely.

A species range is the area where the species can be found. Shifts in these ranges are expected to occur where climate change alters rates of survival and reproduction unevenly across a species' habitats. As conditions deteriorate along one edge of the species' historic distribution (e.g., at lower latitudes and/or elevations), and improve along another (e.g. higher latitudes and/or elevations), range shifts are likely to occur. Species with a high degree of habitat specialization (like old forest specialists) and a smaller natural thermal range are more sensitive to climate change than other species and may be especially prone to move as climates warm (Gardali et al. 2012, Jiguet et al. 2006).

Range shifts have been observed for numerous Sierra Nevada taxa over the past century. Work comparing historic (1914-1920) and contemporary (Moritz et al. 2008) surveys of small mammals conducted in Yosemite National Park by UC Berkeley's Museum of Vertebrate Zoology (MVZ) found that: (1) the elevation limits of geographic ranges shifted primarily upward, and (2) several high-elevation species (e.g., alpine chipmunk; Tamias alpinus) exhibited range contraction (shifted their lower range limit upslope), while several low-elevation species expanded their range upslope (Moritz et al. 2008). Resurvey efforts along two other Sierra Nevada transects showed equivalent elevational shifts for 22 out of 34 small mammals (Rowe et al. 2015). Forister et al. (2010) tracked 159 species of butterflies over 35 years in the central Sierra Nevada and observed upward shifts in the elevational range of species. Tingley et al. (2009) resurveyed bird distributions along the three Sierra Nevada Grinnell transects and concluded that 91% of species followed changes in temperature or precipitation over time and 26% of species tracked temperature and precipitation. Stewart et al. (2017) discovered the extirpation of American pika (Ochotona princeps) from the 64-square-mile Pluto triangle area located in its historical core habitat in the Sierra Nevada. While authors attribute this disappearance to a 3.4ºF warming and significant decline in snowpack since 1910, other studies indicate extant pika populations across a broad range of climatic and environmental conditions, suggesting that non-climatic factors are also at play (Millar et al. 2018). Together, these studies suggest that wildlife are already moving in response to changing climate. To date, it is unclear whether newly arrived species will take on ecological roles associated with past resident species.

3.1.2.3. Novel communities

Climate-driven shifts in species distributions will disrupt communities and create new assemblages with unknown and challenging interactions.

Shifting species' distributions are likely to yield novel assemblages of species in new combinations and, in these novel communities, many species will face new competition or predation, alterations in prey availability, or shifting disease and parasite dynamics (Stralberg et al. 2009). As some species' ranges contract or shift in response to climate or vegetation changes, some species may be released from historical competition with other species (Rubidge et al. 2011). Where climate-sensitive ecosystem engineers and keystone species are eliminated or forced away from

thermally stressful sites, the local ecosystem may lose its integrity and ability to support other species, though the extent to which this may occur in the Sierra Nevada remains unknown.

In addition to direct climate sensitivity, old forest dependent species like the spotted owl, Pacific fisher, and northern goshawk (Accipiter gentilis) may be indirectly impacted by climate change through reduction of populations and distribution of prey species. Declines in moisture (section 2.4) and resulting moisture stress may reduce production of plants, seeds, and fungi that are important food (Seamans et al. 2002; Olson et al. 2004; Glenn et al. 2010 and 2011).

As climate changes, the coincidence between the seasonal timing of species reproduction or migration and the availability of resources to support them may break down (Seavy et al. 2009, MacMynowski & Root 2007). Earlier breeding of California bird communities (by 5-12 days) and overwintering species has been observed over the past century (Dunn & Winkler 1999, Socolar et al. 2017, MacMynowski & Root 2007). In addition to mortality associated with moisture stresses on large trees critical for wildlife species, increases in proportion and patch size of high severity fire have impacted wildlife habitat, particularly over the last half-century.

3.1.3 VULNERABILITY

Although examples of vulnerabilities of natural resources to climate change are described below, a number of Sierra Nevada-based climate change vulnerability assessments have been conducted in the last decade, including NPS, USGS, and USFS (2009); SSP (2010); Koopman et al. (2011); Peterson et al. (2011); Kershner (2014a); and Siegel et al. (2014). They should be consulted for more detail. Once natural resource vulnerability has been assessed and ranked, managers can identify appropriate adaptation actions based on current and desired resource conditions, social and ecological values, management time scales, and feasibility (Peterson et al. 2011).

3.1.3.1 Forests

High elevation forests and old-growth mixed conifer forests are the most vulnerable to projected changes in climate and wildfire. Wildlife species dependent on these habitats are also imperiled.

Projections suggest much of the low- and mid-elevation forests in the Sierra Nevada, where species like owl and fisher reside, are vulnerable to conversion to woodlands, shrublands, and grasslands. Projections of future climate and vegetation conditions using the MC1 vegetation change model (Bachelet et al. 2001, Lenihan et al. 2008) suggest a major decrease in suitable old forest mixed conifer habitat over the next 50 years (Spencer et al., unpublished analyses performed for the Yale Framework Climate Adaptation Project: http://yale.databasin.org/pages/cbi), although these models may not adequately account for topographic effects on local microclimate and vegetation, which may partially mitigate the changes in mountainous terrain. In a recent study (Thorne et al. 2016), trees in the Sierra Nevada forests as a whole were shown to be only moderately vulnerable to projected climate conditions even though the region will experience some of the most extreme shifts in climate in the state because the elevation gradient provides avenues for species to escape "uphill" as the climate warms. However, forests at the highest elevations are more vulnerable simply because there is no place to move as the climate warms.

While we generally have more information on documented and projected climate change impacts on tree species, understory grass, forb, and shrub species will likely also experience dramatic range shifts, expansions and contractions. Many already rare plants will decline (Anacker et al. 2013). Understory plants that are shallow-rooted

are particularly vulnerable, as a change in snowmelt timing disproportionately impacts water availability in the upper soil profile (Blankinship et al. 2014). Lowland non-native shrubs were experimentally shown to expand their range into Sierra Nevada montane zones with reductions in snowpack, which potentially could have cascading impacts on forest understory communities (Stevens and Latimer 2015). Additionally, nonnative plant species from four families were shown to be mostly limited by climate (and not dispersal) currently, implying continued climate change could bring non-native plants to hitherto unoccupied elevations (Rundel and Keeley 2016). Various studies have documented increasing dominance of warm and/or dry-adapted plant lineages in forest understory forbs and grasses. These patterns are driven directly by changes in the climate (Damschen et al. 2010) but also by trends in fire (Stevens et al. 2015). Future warming and increasingly severe wildfires will most likely accelerate this trend.

Projected increases in temperature and decreases in snowpack for the Sierra Nevada are likely to continue the increasing trend in the size of stand-replacing fires and proportion of landscape impacted by those fires (Miller and Safford 2012). In addition to fire-driven vegetation changes, changes in moisture regimes affect important wildlife habitat components. Lenihan et al. (2003, 2008) predict that, under wetter future scenarios, broadleaf trees (especially oaks) will likely replace conifer-dominated forests in many parts of the low- and mid-elevation Sierra Nevada in the next century. Under drier future scenarios, Lenihan et al. (2003, 2008) project that shrublands or grasslands will expand into conifer types, due to drought and increases in fire frequency and severity, thus further reducing old forest habitat.

The projected increases in areas burned (Fig. 3.1.1) and wildfire severity are likely to drive changes in tree species compositions (Lenihan et al. 2003, 2008) and reduce the extent of late-successional forests (McKenzie et al. 2004, Safford and Stevens 2017, Restaino and Safford, in press), which could alter the extent, abundance, or occurrence of species associated with these habitats (McKenzie et al. 2004; Purcell et al. 2012). In the long term, these threats may be somewhat mitigated by mixed-conifer forests moving upslope and the development of habitat for owls and other species where none now exists (Peery et al. 2012). However, development of suitable forest structure at higher elevations will likely take many decades and will not keep pace with climate warming or habitat loss at lower elevations (Stephens et al. 2016). In fact, Stephens et al. (2016) suggest that within the next 75 years, the cumulative amount of spotted owl nesting habitat burned at high or moderate/high severity will exceed the total existing habitat today.

3.1.3.2. Oak woodlands

Development pressures and climate warming contribute to predictions of oak-woodland declines.

By 2040, California's human population is predicted to increase by as much as 27%, posing a formidable threat to oak woodlands of the Sierra Nevada foothills, which are prime real estate (Gaman and Firman 2017). Future conversion of oak woodlands for human development will interact with the impacts of climate change to further alter these systems. By late 21st century, valley and blue oak populations are projected to decline to less than 60% of their former range, while there may be some upward movement of foothill woodlands into higher elevations (Kueppers et al. 2005). Thorne et al. (2008) have already observed conversions of blue oak woodlands to grasslands at lower elevations. In contrast to oaks in the Sierra Nevada foothills, montane hardwood forests are projected to increase in extent with climate change (Lenihan et al. 2008). Montane hardwood forests are becoming more competitive with conifers as a result of a continued increase in high severity fires, increased precipitation and higher temperatures, and nutrient inputs from air pollution (Lenihan et al. 2003, 2008; North et al. 2016). Densities of Sierra Nevada montane hardwood stands have increased by 100% in plots compared from 1930 to 2000, more than any other forest type in

plots compared from 1930 to 2000, with the proportion of plots dominated by hardwoods increasing 100% (Dolanc et al. 2014). During the 2012 to 2016 drought, black oaks had among the highest survivorship of any tree species studied (Pile et al. in press).

3.1.3.3 Montane Meadows

Meadows are particularly vulnerable to disruptions of local hydrology.

Hydrology is the primary driver of community composition and structure in montane meadows (Weixelman et al. 2011). Thus, meadows are particularly vulnerable to disruptions of hydrologic processes. Human activities like logging, road and railroad construction, ditching and channelization, and grazing have impacted the extents and structures of meadows (SNEP 1996, Belsky et al. 1999), and resulting changes in meadow hydrology result in vegetation changes and habitat loss, faster stream flows and therefore a change in timing of water released downstream, stream downcutting and water table declines, conifer encroachment and a gradual loss of meadow extent (Veirs et al. 2013). Climate change, especially the predicted changes in the magnitude and timing of the Sierra snowpack (Section 2.3), will have profound effects on meadow hydrology.

3.1.3.4 Wildlife

Vulnerability to climate change is widespread among wildlife but old-growth forest species are likely the most sensitive.

Significant changes in the Sierra Nevada's terrestrial fauna and flora are projected over the next century. Using species distribution modeling, the California Avian Data Center (CADC 2011) projected that approximately ranges of 60% of 21 coniferous-forest bird species in the Sierra Nevada will be substantially reduced within the next 40 to 90 years. Lawler et al. (2009a, b) projected greater than 50% change in the amphibian fauna and 10-40% change in the mammalian fauna under a high greenhouse-gas emissions scenario. Given the vulnerabilities of forested ecosystems described above, species that require older, denser, and more structurally complex forest conditions, like Pacific fisher and the spotted owl, will likely be negatively impacted by changes in fire regimes and vegetation associated with climate change (Scheller et al. 2011).

3.1.4 ADAPTATION ACTIONS

3.1.4.1 Forests and oak woodlands

A wide-ranging portfolio of adaptation options is available to reduce the vulnerability of Sierra Nevada forests and woodlands to climate change.

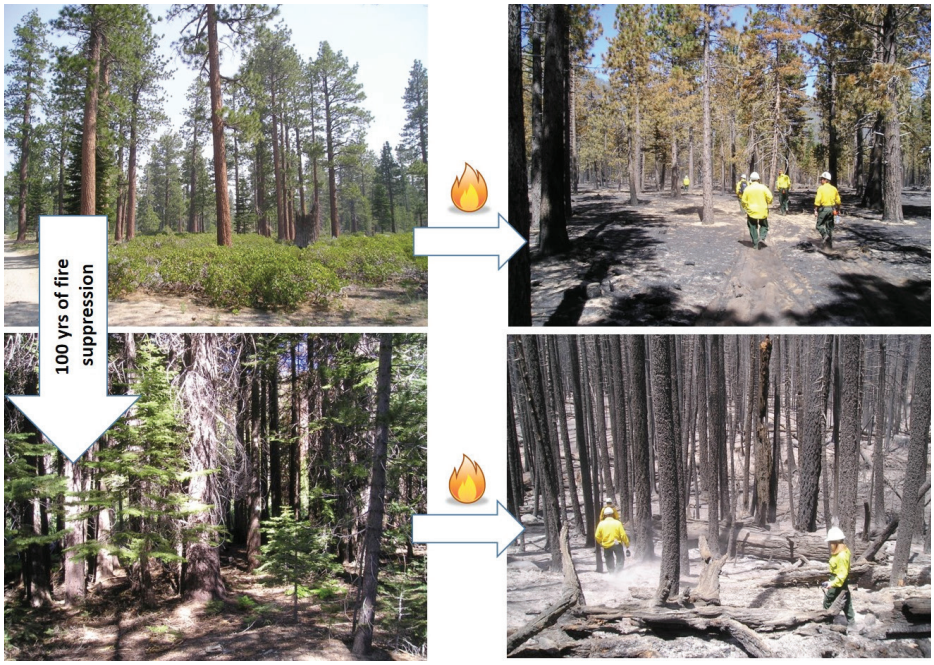
For decades, management objectives of federal and state resource management agencies in the Sierra Nevada have centered on providing and maintaining habitat for a small suite of animal species (e.g. spotted owl, fisher, goshawk) thought to be dependent on dense, complex, old-forest conditions where major ecological disturbances are rare. Ironically, such areas were probably relatively uncommon in the Sierra Nevada region before Euro-American settlement (Safford and Stevens 2017). In areas thought to be necessary for sustainability of these species, a policy of climate change *resistance* is being undertaken, where disturbances are suppressed, and management activities are minimized or avoided. Resistance-based adaptation actions in Sierra Nevada region forests and woodlands include: continued fire suppression; installation of fuel reduction treatments

around high-value habitat; exotic-species control efforts; road hardening and slope stabilization to reduce erosion from increasingly severe storms; and insecticide use to protect high-value trees from insect attack. However, under rapid climate change and associated disturbance trends, resistance-based management of such habitat is becoming increasingly tenuous, and large areas have been lost to fire and insect-related mortality over the last decade (Stephens et al. 2016, Young et al. 2017).

Outside of sensitive habitat areas, forest adaptation actions have focused more on *resilience*, with the goal being the long-term retention of tree cover in currently forested areas. The maintenance of cover (especially conifer cover) protects a variety of ecosystem services, including carbon sequestration, water supply, recreation, rural economies, scenic quality, and soil retention. Resilience is the most-often recommended adaptation objective, and actions currently being undertaken or that could be undertaken in Sierra Nevada region forests and woodlands include (e.g., Peterson et al. 2011, Kershner 2014):

- reducing forest densities to decrease water stress, fire hazard, and insect outbreaks (Fig. 3.1.4);
- managing rather than suppressing wildfires, when possible;
- planting disease-resistant species and genotypes to restore diverse tree compositions;
- increasing connectivity among blocks of forest habitat (not just old-growth), to permit species dispersal and other spatial ecological processes;

FIGURE 3.1.4



Effects of forest restoration on resilience. The photos on the left are just outside the Angora Fire footprint, near Lake Tahoe. The bottom left photo shows the general state of forest in much of the Angora Fire area before the late 1990s. High density and dominance of fire-intolerant species resulted from logging of the pines and forest in-growth during 100+ years of fire suppression. The upper left photo was taken 1600 ft from the bottom left photo in an area that was restored in the late 1990s and early 2000s, using mechanized and hand thinning followed by a pile burn/prescribed fire, transforming the forest to an open, pine dominated stand with much lower fuel loading. The photos on the right show the effects of the Angora Fire in 2007 on the two stand types. Restored forest stands were much more resilient to fire and suffered little loss of canopy or forest biomass. Untreated stands tended to burn much more intensely, resulting in 80-100% tree mortality, severe soil effects, and enhanced invasion by exotic species. Photos by H.D. Safford.

- increasing ecosystem heterogeneity (composition, structure, function) in order to increase ecological "flexibility" and reduce widespread disturbances;
- maintaining seedling stocks sufficient to restore severely compromised ecosystems; and
- managing grazing intensity and timing in hardwood stands to increase recruitment success and to reduce exotic species impacts.

In practice, multiple approaches are applied simultaneously to improve forest resistance and resilience. The ongoing project at French Meadows in the Middle Fork of the American River is an example of resilience-based management (Box 2). Efforts underway in and near the Lake Tahoe Basin (Box 3) demonstrate the multi-institutional alliance needed to effect climate-adaptation at the landscape scale. The Sierra Nevada Watershed Improvement Program (Box 4) provides a region-wide framework for planning and implementing adaptive strategies for entire watersheds.

BOX 2. FRENCH MEADOWS FOREST RESILIENCE PROJECT

The goal of the Nature Conservancy (TNC) of California's French Meadows Project is to promote forest resilience to climate change and reduce the risk of wildfire through mechanical thinning and prescribed fire in an area near the headwaters of the Middle Fork of the American River, west of the Lake Tahoe basin. Using an ecological framework, the TNC aims to treat a large part of the forested landscape, in contrast to strategically placed landscape treatments that target 20-25% of the landscape. Characteristics such as slope, aspect, elevation, soils, and fire probabilities guided the design of restorative treatments (GTR-220, North et al. 2009; GTR-237, North et al. 2012). The project is currently undergoing environmental reviews, with a decision expected in the fall and subsequent implementation beginning in Spring 2019. Over the next five years, prescribed burning will be carried out through a stewardship agreement with Placer County and the US Forest Service to protect infrastructure and to coordinate simultaneous fuel treatments. If successful, this strategy will thin overcrowded forest stands, decrease potential evaporation, and increase available water to remaining trees so they can better resist insects, drought, and fire.

The adaptation strategy aims to improve not only the resilience of the area's mixed conifer forests, but also habitats of the California spotted owl (Strix occidentalis occidentalis) and the federally-listed Sierra Nevada yellow-legged frog (Rana sierrae), which lives downstream from the project site. High-severity wildfires such as the 2013 Rim Fire and the 2014 King Fire devastated owl nesting habitats, and influxes of silt from the Rubicon River after the King Fire killed egg masses of the yellow-legged frog. In this project, areas around owl packs would be thinned by hand in order to reduce the chance of high intensity fire that would degrade suitable owl nesting habitat. The project also aims to quantify the effects of thinning and burning on water yield downstream, which will improve ability of Placer County Water Agency's (PCWA) to protect frog spawning habitat as well as to meet the water-supply needs of their consumers and to provide hydropower.

BOX 3. LAKE TAHOE BASIN ADAPTATION EFFORTS

Climate Adaptation Action Plan

Lake Tahoe has started crafting a new basin-wide Climate Adaptation Action Plan (CAAP) to integrate the activities of its State agencies and partner organizations. Convened by the California Tahoe Conservancy, the CAAP will update the scientific foundation of numerous existing plans with climate change projections scaled down to the Basin, and will explore associated impacts to a wide range of social-ecological values, including resources like the Lake, mountain meadows and streams, forests, and wildlife. They also cover highways and trails, energy and water resources, California Native American connections to the landscape, and the summer and winter recreation and tourism economy. Responding to multiple State mandates, the Plan will link actions that reduce greenhouse gas emissions, increase resilience to extreme events, and adapt to climate trends. Within the Basin, the CAAP will contribute to initiatives that protect water quality and sensitive species, enhance emergency preparedness, restore watersheds and forests while reducing fuels, and eradicate aquatic invasive species. The initiative seeks to combine base funding from the Conservancy with grants from Caltrans, CAL FIRE, California Strategic Growth Council, and other potential sources.

Lake Tahoe West Restoration Partnership

In 2016, a new partnership covering the entire west shore of Lake Tahoe started developing a framework and tools accounting for climate change that will eventually increase the scale and pace of forest and watershed restoration around the Basin. This landscape includes social-ecological values like wilderness areas, trails linking backyards to backcountry, birds and animals, stands of old growth trees, and meadows with rare plants and flowers. Lake Tahoe West's approach builds on the experiences of pioneering collaboratives elsewhere in the Sierra Nevada. The first step has involved assessing the resilience of the landscape to a wide variety of disturbances, including climate change, fire, tree mortality, and drought. The second step involves developing a landscape restoration strategy. By modeling restoration activities at a large scale over the long term, this strategy encompasses all jurisdictions and creates economies of scale. Third, the initiative will plan large projects that encompass all jurisdictions, thereby increasing the efficiency of environmental reviews and permitting. The fourth step will implement restoration, monitor outcomes, incorporate new climate data, and refine subsequent actions. Thereafter, the six state and federal agencies and the foundation that collaboratively lead the Lake Tahoe West Restoration Partnership anticipate using its landscape assessment and landscape strategy templates to rapidly advance large-scale restoration along the Lake's other shores.

Tahoe Central Sierra Initiative

Encompassing 2.4 million acres, the Tahoe Central Sierra Initiative (TCSI) takes a novel approach to restoration by strategically linking six existing forest landscape restoration collaboratives. Rather than duplicate or supplant these endeavors, TCSI focuses on the handful of cross-cutting issues that necessitate working at a very large scale, including operating biomass facilities to help treat forest fuels, protecting wide-ranging sensitive species, using prescribed and managed fire across multiple jurisdictions, and adapting to climate change. TCSI has started identifying common outcomes that characterize resilient forest landscapes across the collaboratives and throughout the region. A subsequent action plan will help to guide and assess restoration work that each agency and collaborative undertakes, and a corresponding data dashboard will help to compare and communicate their successes. The conveners—including the California Tahoe Conservancy, Sierra Nevada Conservancy, the Forest Service Lake Tahoe Basin Management Unit and Tahoe and Eldorado National Forests, and several university and non-profit partners—have already begun jointly securing state and federal funding, and leveraging their complementary authorities, staff, and resources to improve the health and resilience of this region's forests.

BOX 4. SIERRA NEVADA WATERSHED IMPROVEMENT PROGRAM

Sierra Nevada forests and watersheds are at a crucial point. A four-year drought, a century of fire suppression, widespread tree mortality due to insect attacks and disease, and a changing climate have led to an increased risk of large, damaging wildfires. The Sierra Nevada Watershed Improvement Program (WIP) is a coordinated, integrated, collaborative program aiming to restore the health of California's primary watersheds through increased investment and needed policy changes. The Sierra Nevada Conservancy and the U.S. Forest Service, Pacific Southwest Region, are the primary coordinators of WIP, but the program is heavily reliant on active engagement and participation of many other partners. A Memorandum of Understanding between the primary coordinators commits to ongoing, high-level support. The WIP has been endorsed by a diverse group of organizations, as well as other state and federal agencies.

The current level of state, federal, local, and private investment in our forested watersheds is inadequate to meet the need, despite the fact that the costs of overgrown, unhealthy forests are far greater than the costs of the restoration work needed. These former costs include fire suppression, losses of property and infrastructure, other socio-economic costs, and environmental impacts. Opportunities for more reliable funding of restoration in the Sierra Nevada exist but only with coordination among federal, state, and local agencies and private partners. Potential funding sources include State and Federal Funding, and Private or Beneficiaries-Pay Funding, such as social bonds, or "pay for success" financing; valuing ecosystem services; end user water fees; and private and foundation investment targeted at ecological outcomes.

The lack of wood and biomass processing infrastructure in the Sierra Nevada is another significant impediment to forest restoration efforts. Infrastructure projects are integral to WIP because they utilize biomass to provide energy, reduce fire risk, and improve local socio-economic conditions. Enhancements to existing infrastructure will be needed if it is to accommodate the pace and scale of restoration activities envisioned by WIP. To learn more about the Sierra Nevada Watershed Improvement Program, and to access resources such as the Watershed Information Network, visit www.restorethesierra.org.

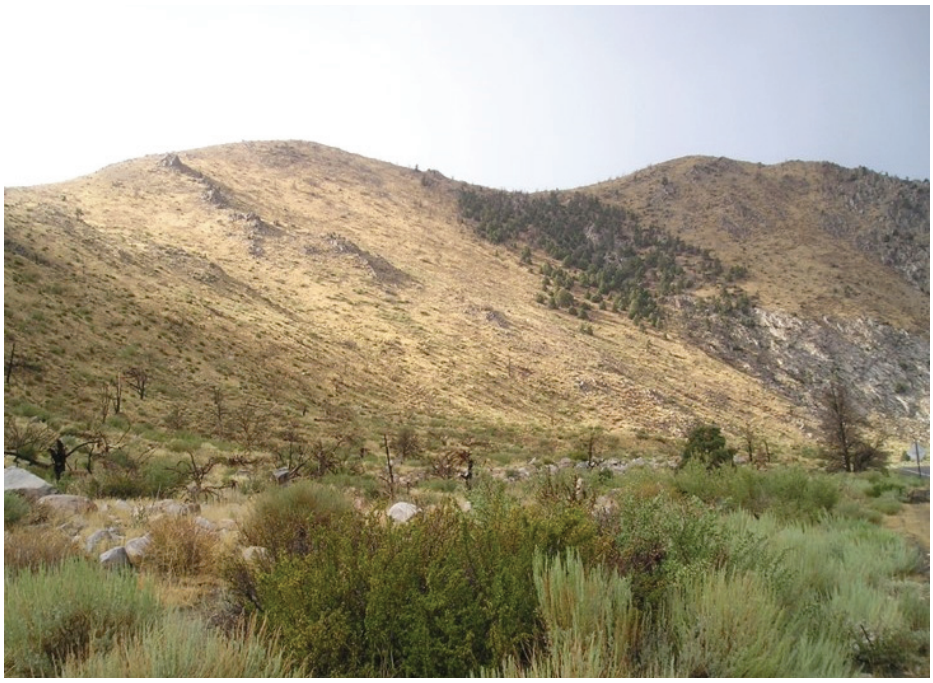
There are relatively few current examples of proactive *response* adaptation in the Sierra Nevada, but as the climate changes, decisions to assist transitions to novel ecosystem states that continue to provide important ecosystem services and/or habitat may need to be made (section 3.1.3.3). Options include:

- assisted migration/managed relocation of species to locations beyond native ranges but where current climate is favorable or where the future climate is projected to be so;
- planting genotypes drawn from areas already characterized to be like the future climate;
- promotion of hardwood/broadleaf species in settings currently dominated by lower-elevation conifers;
- cessation of planting or protecting species where their sustainability is highly doubtful;
- increase ecosystem connectivity to facilitate migration in response to climate change; and
- decommissioning roads and trails in locations where large and recurrent climate change-related impacts (like flooding) are likely.

Realignment strategies generally involve more input of energy and resources. Highly disturbed sites often provide the opportunity to reset ecological trajectories (Fig. 3.1.5). Often, ecological restoration projects involve ecosystem realignments. Examples include:

- restoration of mine sites and other seriously disturbed locations to conditions that are sustainable under future climatic conditions;
- restoring single-species plantations to more diverse and heterogeneous forest stands; and
- planting of new species in deforested sites where previous dominant species are not regenerating.

FIGURE 3.1.5



This Topaz Lake site was burned in 2002. The mountainside here was dominated by pinyon pine before the fire. Photo was taken in 2014 and there is almost no pine regeneration. The tan colored area is covered in grass (exotic cheatgrass and brome, and some native grasses), and the likelihood of further fires is very high, given fine-fuel loading from the invasive grass, proximity to a road (human ignitions), high lightning strike density, and warming summers. Such sites provide opportunities for realignment management, with serious consideration to which (semi-)natural ecosystems might be sustainable and which ecosystems services are desired. Photo by H.D. Safford.

3.1.4.2 Meadows

Relatively low-impact means exist to improve resistance and resilience in montane meadows, while re-alignment involves more intrusive approaches.

Climate change adaptation in meadow ecosystems can involve:

- resistance actions, like removal of tree seedlings encroaching into meadows (Fig. 3.1.6);
- resilience actions, such as managing livestock grazing to reduce soil compaction and permit natural restoration of stream banks;
- response actions, including permitting tree encroachment to occur, or deciding not to control invasive species that are providing similar ecosystem services to native species; and
- realignment actions, like damming stream headcuts to reduce erosion and raise water tables, re-engineering of stream sinuosity, or diversion of water to maintain wet meadows and fens.

FIGURE 3.1.6

Tuolumne Meadows in Yosemite National Park. Lodgepole pine seedlings constantly invade the meadow, partly because the meadow water table is dropping due to changes in the climate. Park staff remove seedlings every few years to protect the open nature of the meadow. This is an example of a resistance strategy in climate change adaptation. Photo by H.D. Safford.

Box 5 offers some examples of ongoing efforts to improve both the resistance and resilience of mountain meadows. Prioritization of meadow restorations might usefully be focused on meadows that may serve as climatic refugia (i.e., areas predicted to experience less change in temperature), wetter meadows that are naturally more resistant to conifer encroachment, and meadows that provide habitat connectivity for species of interest (Maher et al. 2017, Lubetkin et al. 2017).

BOX 5. EXAMPLES OF MEADOWS RESTORATION EFFORTS

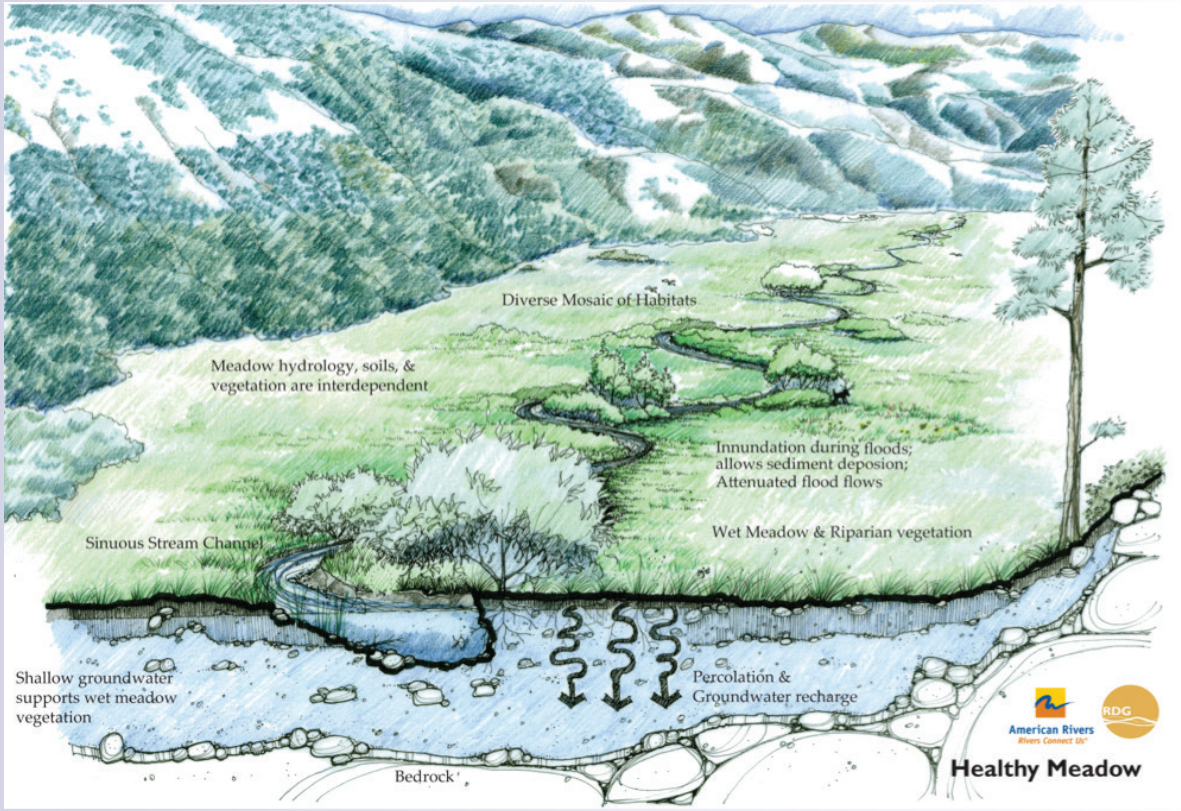
With increased flooding, reduced snowpacks and snowmelt, forest and habitat change (if not out-right loss), and longer drier summers projected to result from climate change, the benefits that accrue from meadow restorations will be of even greater value in the future. Added groundwater storage, improved maintenance of meadow and downstream baseflows, reductions in channel erosion and soil losses, more robust opportunities for meadows to serve as climate-change refugia (Morelli et al. 2016), carbon sequestration (Zhu and Reed 2012), and cleaner water that result from meadow restoration will all help place the Sierra Nevada and downstream water users on much firmer ground to resist and adapt to the coming climate change.

The Sierra Meadows Partnership is a consortium of over 26 partner agencies focused on advancing meadow research and restoration efforts, developing restoration protocols and strategies, and establishing funding mechanisms including implementation of a meadows carbon credit market. The institutions and agencies involved—some of which have been pursuing these goals for decades—work to connect meadow-restoration efforts with more traditional land users, to improve information transfers, to develop best-management practices, and to ensure long-term monitoring of landscape and ecological responses to restoration.

Mountain meadows also carry cultural significance because they are home to plants that provide food, medicine, and materials for some tribal groups. The Native Youth Conservation Corps works with partners to restore meadows groundwater storage capacity, increase habitat connectivity, preserve cultural resources, and improve ecosystem resilience to climate change. They integrate Traditional Ecological Knowledge into headwaters management (CNRA 2016a).

In 2016, California Assembly Bill 2480 identified mountain meadows as significant parts of the state's water infrastructure, allowing meadow restoration efforts to compete for the same funding sources as other water conveyance and treatment facilities. Millions of dollars are now invested in meadow restoration annually, from federal, state, and private sources. The State and Forest Service have set ambitious goals including restoration of 10 thousand acres by the California Department of Fish and Wildlife, and another 50 thousand on National Forest lands, over the next decade.

BOX 5—CONTINUED. EXAMPLES OF MEADOWS RESTORATION EFFORTS



Idealized conditions in healthy meadows; figure used by permission of American Rivers.

3.1.4.3 Wildlife

Adaptation strategies for vulnerable wildlife species should emphasize strategies that protect climate refugia and that maintain migration corridors.

Climate change may reduce the capacity to adapt directly (e.g. changes in genetic diversity) or indirectly (e.g. changing habitats). Some management and conservation actions can increase adaptive capacity –for example, protecting or increasing refugia, reducing moisture stress on key habitat features, reducing fire risk, and increasing habitat connectivity– may aid species adaptation under changing environmental conditions.

Genetic evidence suggests that fishers have survived climate-driven range contraction in the past, and that the southern Sierra Nevada may have served as a climate refugium that supported that past survival (Tucker et al. 2014). Looking to the future, Loarie et al. (2008) identified the southern Sierra Nevada as a potential climate change refugium. Loarie et al. (2008) and Lawler and Olden (2011) recommend novel adaptive management approaches and large-scale planning efforts that promote landscape/regional habitat connectivity. To protect fisher habitat, Lawler et al. (2012) advocate targeted forest-fuel treatment and applying more liberal fire-management policies to naturally ignited fires during moderate weather conditions. Morelli et al. (2016) suggest that active fire and fuel management could be prioritized to protect climate change refugia from, or enhance resilience to, extreme fires that otherwise might damage the ecosystem irreversibly.

Morelli et al. (2016) present a framework for managing refugia for climate change resistance and resilience, emphasizing that the approach is a way for managers to prioritize areas for conservation and climate adaptation, particularly where refugial characteristics for a set of valued resources may coincide (Morelli et al. 2016). However, they also note that climate change refugia and resistance strategies are not long-term solutions. Refugia might only be relevant for a certain degree of climatic change, after which they no longer support conditions necessary for the populations they are designed to protect. Thus, refugia "function best when coupled with contingency plans, such as tracking geographic shifts in refugial habitats to keep pace with climate change or maintaining genetic material in seed banks, captive propagation, or zoos for future re-introduction" (Morelli et al. 2016).

3.2 Water Resources

Climate-change impacts on Sierra Nevada water resources will be important for both local communities and for millions of downstream water users in the Central Valley and more distant parts of the state.

Almost 75% of California's water resources originate in Sierra Nevada snowpack (DWR 2008). This natural reservoir captures and stores water in the winter, when it is least needed, and slowly releases it in spring and summer through snowmelt and streamflow, when precipitation is limited and statewide water demands are high. Climate-change impacts on the amounts of snowpack and timing of snowmelt and streamflow (Section 2.3-2.4) are expected to impact both the quantity and quality of water resources available to downstream urban and agricultural users, including three million acres of agricultural land irrigated from the Sacramento-San Joaquin Delta (http://www.sierranevada.ca.gov/our-region/ca-primary-watershed). Spring snowmelt and streamflow provide water for natural and human communities from the Sierra Nevada west to the California coastline and east into the deserts of easternmost California and western Nevada. At higher elevations, snowmelt is the primary source of water for local communities and montane habitats.

Connections between downstream water users and upstream headwaters communities are important. The infrastructure used to move and deliver this water includes dams, aqueducts, and levees used for multiple purposes, and is one of the largest water infrastructure systems in the nation. Some infrastructure serves several purposes. Dams store water through the winter for release during the summer dry season and also provide flood control and year-round hydropower generation. Levees and waterways in the Central Valley and San Francisco Bay-Delta system protect against flooding and ensure high-quality habitat for species such as the Delta smelt (*Hypomesus transpacificus*).

Though human populations are generally smaller and more remote than in other regions, water is very important to Sierra Nevada communities for residential, commercial, and agricultural uses; recreation (fishing, boating, rafting, skiing, and more); and for water-related habitats, including meadows, riparian regions, lakes, and rivers. Water is a major driver of the tourism-based economies and livelihoods in the region, though these uses garner less attention than better known urban and agricultural uses downstream.

Because Sierra Nevada populations are dominantly rural and, in many places, disadvantaged, water resource management is challenged by lack of human and financial resources.

Water resource management in rural and/or disadvantaged communities (DACs) can be especially difficult (see Section 3.3). Residential and commercial water supplies are mostly provided by small public and private water systems. Because of the rural and remote nature of these communities and their water systems, many have limited access to resources for water management. They may or may not have paid staff. Water operators, if paid, are often only employed part-time or may be shared by several systems. Systems' board members are typically members of the community and may not have experience with water resources management. It is difficult for small and DAC systems to keep up with capital improvements and regular maintenance. It is not uncommon to hear from water managers that Prop. 218 (which expanded voter-approval requirements for local government taxes) has made it difficult for some small water systems to raise rates in order to fund much-needed maintenance and improvements.

3.2.1 CLIMATE EFFECTS, TRENDS AND PROJECTIONS

3.2.1.1 Climate Trends and Projections

Temperature and precipitation changes will lead to direct impacts on the regional water cycle, including uncertain changes in natural water demands.

Increasing temperatures leading to a greater fraction of precipitation as snowfall rather than rainfall, smaller snowpack, decreased snow-water equivalent (SWE), and earlier snowmelt, along with increases in extreme weather events, already loom over water management in the state (Section 2; Feng and Hu 2007, Barnett et al. 2008, Wang et al. 2017, Mote et al. 2018).

Water resources will be impacted most directly by changes in the water cycle. As noted in section 2.2, projected changes in annual precipitation are not as consistent as projected temperature trends, and projected average precipitation changes in the Sierra Nevada are small compared to naturally large year-to-year fluctuations in the region. In addition to changes in precipitation averages, extreme precipitation events—such as large storms, rain-on-snow, and drought—are expected to increase in magnitude and frequency. It is also expected that, due to complex geography, changes in precipitation and hydrology will not be uniform across the Sierra Nevada.

In drier areas, particularly in the Eastside subregion (fig. 1.1a), a delayed onset of the summer North American monsoon with subsequent increases in late summer precipitation is projected (Section 2.2; Meixner et al. 2016). Another pressure on water resources will likely come from increases in evapotranspiration (Cayan et al. 2013), the

combination of evaporation from soils, plants and water surfaces, and water use by plants. Warmer air temperatures will lead to longer growing seasons and increased evaporative demands on soil moisture and plants (section 2.4). Some of the potential for increased water use by plants may be mitigated by the capacity of plants in higher concentrations of atmospheric CO2 to use water more efficiently by narrowing their stomatal openings (pores through which plants take in and emit air and water vapor; Keenan et al. 2013). On the other hand, this "fertilization" effect of increased atmospheric CO2 may be limited by low nitrogen inputs in the Sierra Nevada (Norby et al. 2010), or may lead to more plant growth or denser stands of plants, yielding increased overall plant-water demand (Liang et al. 2017). This confusion of potentially counterbalancing plant responses to warming and CO2 remains a significant uncertainty for future Sierra Nevada streamflow, recharge, water supplies, and vegetation health.

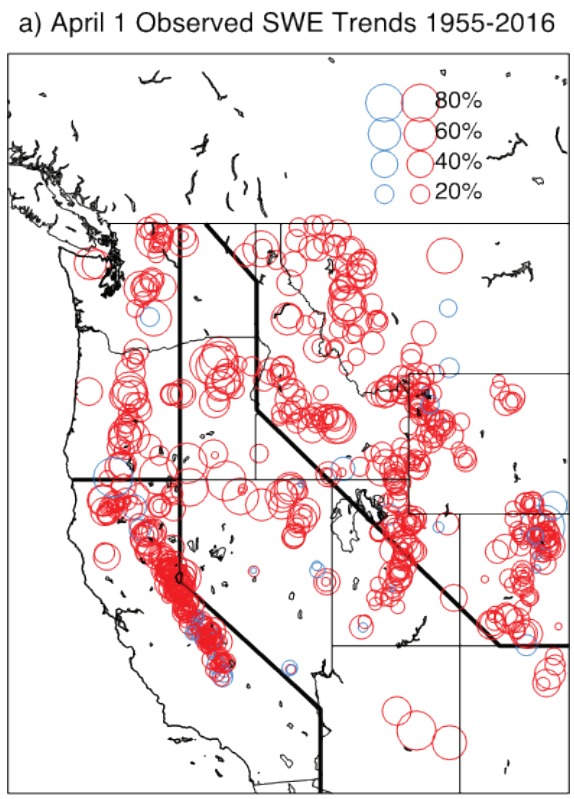
3.2.1.2 Snowpack

Snowpack losses are already underway in the Sierra Nevada, as in most of the western US.

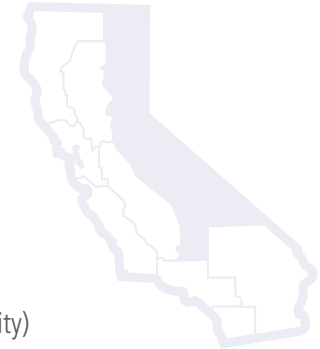
Snowpack and snow cover are expected to continue to decline in most areas of the West as a result of increased winter rains (at expense of winter snowfall) and more winter snowmelt due to higher temperatures (section 2.3; Bales et al. 2014; Knowles 2015). The standard predictor of the amount of water that will be available for warm-season supplies (observed April 1 SWE) has already declined throughout the West, although not uniformly so (Mote et al. 2005). During the past 65 years, the largest losses in April 1 SWE have occurred in Washington, Oregon, and northern California, including the northern Sierra Nevada. Long-term declines are also occurring in the southern Sierra Nevada, which appeared in earlier studies (Mote et al. 2005) to be experiencing increasing SWE. The addition of another 10 years of data has now clarified that long-term declines have occurred up to its highest reaches (Mote et al. 2018; Fig. 3.2.1). For the future, overall declines in SWE are expected to continue and even accelerate (Section 2.3, Figs. 2.5-6).

The largest declines in SWE are projected to occur in those lower- to middle elevation parts of western mountain ranges where winter temperatures currently hover near freezing (Fig. 2.4; and Kapnick and Hall 2012). Notably, a much larger fraction of the snow zone of the eastern slope of the Sierra Nevada is at higher elevations than on the western slope. This greater proportion of watersheds at elevations above those most likely to be impacted by changes in freezing level may moderate the impacts of rising temperatures on snowpacks on those eastern slopes (Fig. 2.8d; Ficklin et al. 2012).

FIGURE 3.2.1



Linear trends in 1 April snow-water equivalent (SWE) relative to starting value for the linear fit at 699 snow course locations in the western US, for periods of record between 1955-2016; diameters of circles are proportional to percentage change, with red indicating declining SWE and blue indicating increasing SWE (from Mote et al. 2018).



3.2.1.3 Floods

Flood risks are projected to increase under climate change, challenging some existing water (and community) infrastructures.

The Sierra Nevada is the source of most of California's water resources but, on the whole, is also the source of its largest floods. Increased incidence of winter rainfall, "cool" season snowmelt episodes, and rain-on-snow events are projected to increase winter flooding even as they increase the average winter streamflow rates (section 2.4; McCabe et al. 2007; Das et al. 2013). In the lower-elevation Northern Sierra Nevada, rain already reaches up to ridgelines in historical warm storms, so that more warming is less likely to increase the areas that contribute rainfall runoff to the largest floods. In the higher Southern Sierra Nevada, however, above-freezing conditions during historical warm storms generally do not reach the ridgelines so that large additional areas remain to be subjected to rainfall in warmer future storms. As a consequence, warming is likely to increase the frequency of flood-generating conditions in the northern Sierra Nevada but is likely to increase both frequency and magnitude of floods from the southern Sierra Nevada. In addition to these effects of warming, the largest storms are projected to become even larger (Fig. 2.3), which, in combination with trends towards more precipitation falling as rain, are also projected to increase Sierra Nevada flood risks and magnitudes (Dettinger 2011; Das et al. 2013; Stewart et al. 2015). Many Sierra Nevada communities do not have the infrastructure in place to deal with enhanced winter floods. These same floods also stress downstream conveyance, reservoirs, and communities, as exemplified by the Oroville Dam crisis that occurred in February 2017. Changes in the amount and seasonality of runoff will place more stress on ecosystems that are adapted to the current rainy season/dry season dynamics. Similarly, increased monsoonal activity in parts of the region, including especially the Eastside subregion (Fig. 1.1a) may stress local storm water and flood management systems.

3.2.1.4 Surface Water

Snowmelt timing will challenge some water-management operations and infrastructures, and the future of annual surface-water amounts remains uncertain.

In response to recent warming trends, changes in snowmelt timing have been observed in rivers all over western North America with peak streamflow in snowfed streams having shifted 10-30 days earlier since 1948 (e.g., Fritze et al. 2011); changes in total streamflow are not so clearly indicated. These observed and projected changes in streamflow timing are most likely caused by warming air temperatures rather than by changes in precipitation amounts (Stewart et al. 2004). These changes are projected to continue and accelerate as climate change, especially warming, accelerates in coming decades. In the Sierra Nevada region, most climate-change projection and impact studies have been conducted on the west slope. A good example of the findings from these studies is the work of Null et al. (2010). That study projected, using the Water Evaluation and Planning tool, that west-slope Sierra Nevada watersheds and water systems in the north are most vulnerable to decreased mean annual flow. Those in the south-central region of the Sierra Nevada are most vulnerable to changes in runoff timing, and the central Sierra Nevada is most vulnerable to longer periods with low streamflow. Although Null et al. (2010) were able to draw some generalized conclusions about broad regions of the Sierra Nevada, they also concluded that it is necessary to take a watershed-by-watershed approach when analyzing changes and impacts.

Two studies on the east slope of the Sierra Nevada focus on watersheds important to the Los Angeles Aqueduct and the City of Los Angeles. Costa-Cabral et al. (2012) modeled the Mono Lake and Owens River watersheds, focusing specifically on impacts of changes in surface water availability for the Los Angeles Aqueduct. Using projections from 16 climate models to drive the same large-scale hydrology model used in sections 2.3-2.4 as applied to the eastern Sierra Nevada watersheds, they projected that timing of streamflow will be 9 to 37 days earlier in the spring by 2070-2099. They found that precipitation changes (rather than simple warming) were the dominant influence affecting April 1 SWE in these east-slope watersheds, through increased winter rain events and decreased annual snowpack. Ficklin et al. (2012) modeled the Mono Basin using a different hydrologic model and found that annual evapotranspiration increased, resulting in declines in streamflow by 15%, a one-month earlier peak snowmelt and runoff, declines in frequency of wet hydrologic years, and more frequent droughts. Comparing Ficklin et al.'s (2012) projection of annual-streamflow declines to the results in section 2.4 (table 2.4) illustrates the fact that these annual-total projections are sensitive to the climate and hydrologic models used and thus remain uncertain. Most projections are for small changes in total streamflow from much of the Serra Nevada mountains compared to other watersheds in the Western US (Das et al. 2011), but uncertainties still remain.

Farther north, Huntington and Niswonger (2012) simulated generally similar trends as well as reductions in summer groundwater inflows (by 30%) in Third, Incline, and Galena Creeks around the Lake Tahoe Basin, results that have been borne out at larger scales in the US Bureau of Reclamation Truckee River Basin Study (2015). Such complex, multi-faceted, and localized results complicate the task of adapting water management across the region.

3.2.2 VULNERABILITY

3.2.2.1 Surface-Water Supplies

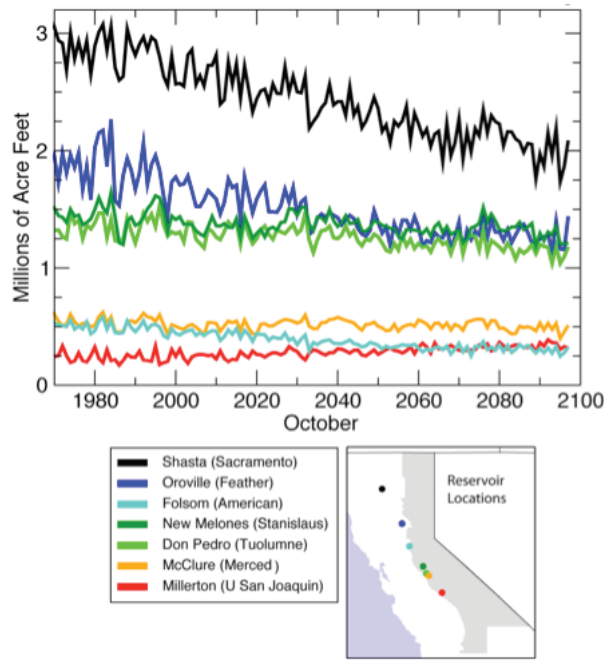
The seasonal availability of surface-water supplies will change, with potentially large impacts on local to state-scale water management systems.

The impacts of a changed climate on surface water amounts and timing in the Sierra Nevada have important implications for water supplies. Observed trends towards earlier peak streamflow will likely continue through the 21st century, with peak streamflows arriving 20-40 days earlier than the mid-20th century in many rivers (Stewart et al. 2004, Fritze et al. 2011). Eventually, warming will drive snowmelt into the earliest spring and latest winter months, when the sun is not high in the sky, so that ultimately snowmelt is likely to slow (Musselman et al. 2017). Nonetheless, earlier peak streamflow will result in greater winter flows with attendant enhancements of flood risks, and less streamflow in the longer, drier summers. Declines in summertime streamflow are particularly important because California's Mediterranean precipitation regimes is such that it routinely experiences a "seasonal drought" in summer, a highly predictable dearth of precipitation during the warm seasons. This summertime drought coincides with when both natural and human communities rely on water reserves stored in snowpack or reservoirs to survive until the next wet season. This is when the fuels that support wildfires cure to their driest points. Thus reductions in summertime surface-water availability place the water supplies for natural and human communities at great risk, as well as elevating wildfire risks.

As the source of so much of California's water, management of the Sierra Nevada region's water resources is key to managing water supplies throughout the region and throughout the State. With projected changes in snowpack, snowmelt and streamflow timing (Fig. 2.8), flood risk, evaporation rates, groundwater, and upstream water uses, even

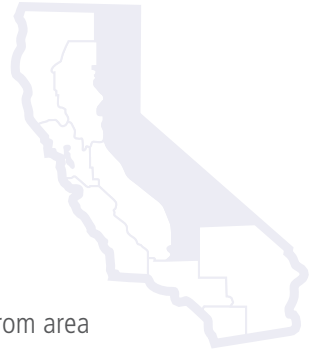
the state's largest scale water-storage and conveyance systems may be challenged. Knowles et al. (in review) simulated the effects of the same 10-model ensemble of climate projections presented in Section 2 on water conditions in a modified version of the U.S. Bureau of Reclamation (USBR) and California Department of Water Resources's CALSIM II model of water-management operations by the State Water Project (SWP), USBR's Central Valley Project (CVP), and other less extensive water supplies and conveyances in the Central Valley. The amount of water stored in the major reservoirs of the western Sierra Nevada by the end of the water year (the "carryover storage") gives a useful indication of the resilience of the large-scale systems to manage long-term drought shortages. Fig. 3.2.2 shows that, on average over projections from ten climate models responding to RCP4.5 and RCP8.5 greenhouse-gas forcings, carryover storage in the largest reservoirs (i.e., Shasta at the head of the CVP and Oroville at the head of the SWP) decline markedly, by roughly one-third over the course of this century. This decline in carryover storage will severely impact reservoir operations, limiting their capacity to ensure adequate water supply for dry years. Declines are smaller farther south, becoming almost nonexistent south of the American River basin (Folsom). Presumably, large declines in the northern Sierra Nevada reflect the dramatic reduction of seasonal storage in the snowpacks of that lower, warmer part of the range (Figs. 2.5 and 2.6). Farther south, snowpacks survive somewhat better, and constraints on reservoir releases to the San Joaquin River and water users in the San Joaquin Valley are such that reservoirs continue to serve at least this most basic of reservoir functions (carryover storage) throughout the century.

FIGURE 3.2.2



Projected end-of-water-year storages in seven major reservoirs along the western ramparts of the Sierra Nevada (see inset map), from combination of 10-model climate-change ensemble, the Variable Infiltration Capacity hydrologic model, and a modified version of the USBR/DWR Calsim II water-management model (based on data from Knowles et al., in review).

The State's large-scale systems provide options for tradeoffs in the face of climate challenges that many of the smaller water-supply systems do not have, so that, more locally, water-supply vulnerabilities are likely to be even more severe than Fig. 3.2.2 suggests and will be much more site-specific and varied. Notably, a simpler analysis of responses to earlier snowmelt by reservoirs near the headwaters of the Truckee River, on the east side of the Sierra Nevada from the drainage supplying the Folsom Reservoir, with modest operational changes that yielded no discernible declines in end-of-summer storage (Sterle et al. 2017), not so much unlike the lack of declines in the reservoirs of the southern Sierra Nevada in Fig. 3.2.2.



3.2.2.2 Groundwater

The vulnerability of groundwater supplies to climate change is less well understood but probably will vary from area to area. Groundwater plays particularly important roles in the volcanic-rock aquifers of the northernmost Sierra Nevada and Northeast subregion.

As important as surface-water changes, but much less well-understood, are the vulnerabilities of groundwater supplies to climate change. Changes in timing, amount, and form of precipitation and streamflow will alter aquifer recharge patterns (Meixner et al. 2016), including recharge to valley alluvial aquifers. It is uncertain how surface-water changes will affect fractured bedrock aquifers, high mountain springs, and headwater stream sources, on which many Sierra Nevada communities rely. There is limited understanding of recharge processes and groundwater flow in mountain blocks (Earman and Dettinger 2008; Meixner et al. 2016). However, as surface water supplies become more variable and unpredictable, communities, landowners, and resource managers will likely turn to groundwater to make up water supply deficits, leading, in some areas, to more intensive groundwater extraction and additional overdrafts (Georgakakos et al. 2013). Groundwater pumping generally requires more energy use than most surface-water supplies, which would increase demands for electricity. More knowledge is badly needed to understand the role of groundwater in the changing hydrology of the Sierra Nevada. The recently enacted Sustainable Groundwater Management Act process and requirements have the potential to increase understanding of groundwater resources and their uses.

Groundwater inflows are particularly important to rivers among the volcanic-rock aquifers of the northernmost Sierra Nevada and Modoc Plateau (Northeast subregion, Fig. 1.1a). Using streamflow records for the last 60 years, Gary Freeman of Pacific Gas and Electric has documented a loss of 400,000 acre-feet from the Feather River at Oroville Dam relative to long-term normal inflows, as groundwater and surface-water contributions to reservoirs have diminished. According to Freeman (personal communs. 2008), climate changes have likely contributed to these losses, but changes in density of vegetation and transpiration may be contributing at least as much.

3.2.2.3 Drought

Water resource management often comes down to drought management in California, and climate change will only exacerbate that challenge.

Climate change is also likely to exacerbate the region's frequent and severe droughts (Section 2.4; Cayan et al. 2013; Ault et al. 2014). Declines in precipitation, and shifts from snow to rain, cause snow drought (Harpold et al. 2017; Hatchett and McEvoy 2018), which further impacts spring runoff, streamflow reliability, and groundwater recharge. The result is that local water resources are less reliable, and downstream water supplies—local and distant—become more uncertain and unpredictable. Drought also impacts local and regional water-based tourism and recreation. Skiing, boating, fishing, and backcountry travel are all impacted by reduced snowpacks, streamflow, and lake storage. Drought can also concentrate contaminants in rivers and lakes, further impacting the habitats they provide. Forests that experience drought are more susceptible to stand-altering wildfires and pest such as bark beetle (Section 3.1). Loss of forest due to wildfire or tree mortality leads to changes in overall yield of streamflow and groundwater (Goulden and Bales 2014), to erosion, and to altered water quality. Depending on their source waters, groundwater systems can be buffers against long- and short-term droughts, but ultimately the relatively small and often isolated aquifers of the mountainous parts of the Sierra Nevada region are vulnerable to changes in recharge and in water

extractions that come with drought. For example, some domestic wells in Bishop went dry during the 2012-2016 drought, necessitating drilling of deeper wells or use of alternative water supplies. The aquifers in the Northeast and Eastside subregions (Fig. 1.1a) tend to be larger with more groundwater storage, but many are tied directly to recharge from the eastern Sierra Nevada and thus are vulnerable to drought impacts there.

3.2.2.4 Water quality

Climate change may impact the region's water quality in a large number of ways, all still quite uncertain.

Surface water may be vulnerable to climate change in the form of alterations and degradation of surface-water contaminant concentrations, pH, dissolved oxygen, and temperature. Increased air temperatures generally lead to increased water temperatures in many stream and lake settings, resulting in declines in dissolved oxygen and degraded habitats for many native aquatic species (Coats et al., 2006; Ficklin et al, 2013; Null et al. 2013). Reductions of summertime streamflow may lead to seasonal increases in contaminant concentrations and water temperatures, further stressing aquatic and riparian habitat and their attendant species. Increased extreme precipitation events led to greater flooding and erosion, impacting surface water quality and surrounding habitat. As an example, the community of June Lake uses surface water from the lake as one of its municipal water sources. During the 2012-2016 drought, water levels in June Lake dropped by 20 feet. As the inflows and water levels dropped, uranium entering the lake from natural sources increased in concentration, causing the municipal water supply to exceed drinking-water limits for uranium, requiring the June Lake water system to implement an additional water treatment step. In addition, stormwater can cause erosion and convey contaminants, threatening the quality of surface water.

3.2.2.5 Water demand

Water demands, both within the region and statewide, will likely be impacted by climate change; the future of Sierra Nevada water-resources management will depend on managing both.

Local residential and commercial water demands in the sparsely populated Sierra Nevada region are small relative to overall supply. Agricultural demands in some areas have exceeded groundwater supplies requiring deepening of wells. Residential demand fluctuates seasonally to meet landscape irrigation, which could increase as summers become longer and warmer. Increased unreliability of surface water may lead to more groundwater extraction for local use, with implications for potential overdraft and decreased groundwater quality. Better data are needed to understand the current groundwater situation, particularly in fractured rock aquifers of the Northern Sierra Nevada, and to understand potential changes in amount and quality.

Downstream, in the Sacramento and San Joaquin Valleys and Southern California, impacts on water resources from changes in the Sierra Nevada may become very significant. Increased air temperatures, particularly in the summer, will mean increased demand for landscape and agricultural irrigation, as well as cooling processes such as air conditioning. Uncertainty in downstream communities about the sustainability of local water resources and other sources of imported water may cause these users to draw increasingly from water supplies in the Sierra Nevada. Communities that maximize their local supplies can help to take pressure off Sierra Nevada supplies.

3.2.3 ADAPTATION ACTIONS

Adaptation of water resources management to a highly variable climate is not new in California, but managers now face rates and magnitudes of change not seen in the history of the state.

Water resources management in the Sierra Nevada will need to adapt to this new reality. Although water managers have always had to deal with major extremes and uncertainties related to climate and weather, which in turn translate into changes and uncertainties regarding water availability and water demand, the magnitude and rate of some of the projected changes are unprecedented. Water management will need to become more responsive and innovative. Local water purveyors will need to develop more nimble operations.

More broadly, California's regional and state-scale water systems that rely directly on water sources in the Sierra Nevada, including its many dams, reservoirs, aqueducts, and pipelines, will be strained as the state reacts to future drying conditions, extreme precipitation events, and changing timing of snowmelt and streamflow.

New surface-water storage in new or expanded reservoirs are frequently discussed as adaptation options, but remain a source of friction between water purveyors (and flood managers) and local resource and conservation communities. Conjunctive-use and other groundwater options are important considerations in those discussions of new storage options.

In response to floods, droughts, and water-temperature requirements that climate change will exacerbate, the California Water Action Plan (2016), among other interests, has identified a need to expand the state's water storage capacity, on many scales and in many areas. Additional surface storage in new or expanded reservoirs is an adaptation alternative that is often discussed in the context of climate change, much like the resistance or resilience options being used to mitigate climate effects on ecosystems in section 3.1. Some existing reservoirs are losing storage capacity to sedimentation, storage that dredging might restore. However, dredging can bring contaminants from the region's mining past back into waterways and supplies with detrimental health consequences. New reservoir storage is an option that tends to pit managers of major water systems against many in the region's communities who are concerned about local, within-region impacts of reservoirs on upstream and downstream communities and aquatic and riparian habitats (e.g., Collier et al. 2000, Nevada Irrigation District 2016, Weiser 2017). The present assessment has little to add to these considerations, except to conclude that the coming challenges from climate change have the potential to be extreme (e.g., Fig. 3.2.2) and that concerns on both sides are very real. More aggressive uses of surface-water and groundwater supplies managed in conjunction with each other offer increased climate-change resilience through use of underground storage, and may provide at least partial substitutes for large new surface-water reservoirs. Underground storage can be much harder to manage and parse within current water law and in large interconnected aquifers like the Central Valley, but is potentially a very effective tool in the climate change-water adaptation toolbox. A principle limitation on storing large quantities of surface water in the state's depleted aquifers will be the need to expand conveyance and recharge facilities/areas so that generally brief but vast flood surpluses can be delivered from where they appear naturally (e.g. the Northern Sierra Nevada and Sacramento Valley) to where the aquifers are most depleted in the San Joaquin Valley (Hanak et al. 2018). The need for additional water storage remains contentious and will benefit from more information and more transparency. Whether these responses are

short-term stop gap measures or offer long-term resistance to climate-change impacts will mostly be a matter of how far global and regional climate changes are allowed to progress; if climate-change impacts grow too large, major adjustments to what we demand of our water systems may be needed.

The Integrated Regional Water Management Program and the Sustainable Groundwater Management Act provide two avenues for developing and implementing needed adaptations.

Programmatic changes have been made at the state level that can help state and local water managers to forestall and accommodate some climate-change impacts through a full range of adaptations from resistance strategies to (at the extremes) realignment actions. In response to a wide variety of water challenges, a handful of statewide programs emerged in the late 1990s and early 2000s to address water-related issues through community-driven approaches at watershed or more regional scales, including the CalFed Watershed Program, Department of Conservation (DOC) Watershed Coordinator Program, and the Integrated Regional Water Management (IRWM) Program. The IRWM Program is still active today and is making its mark in every corner of the Sierra Nevada region. Beginning in 2002 with voter-approved Proposition 50, the State has required that stakeholders managing water must gather at the regional level to develop Regional Water Management Groups in order to be eligible for certain State funding opportunities. Propositions 84 (2006) and 1 (2014) provided funding for the continuation of IRWM at both State and regional levels. As of 2016, 48 IRWM regions have been formed, covering more than 87% of the State's land area and 99% of the State's population (DWR). The Sierra Nevada region contains part or all of 14 IRWM regions, and the entirety of the Sierra Nevada comprises another IRWM region:

North Coast	Tuolumne-Stanislaus
Upper Pit River	Inyo-Mono
Lahontan Basins	Yosemite-Mariposa
Upper Feather River	Madera
Consumnes, American, Bear, Yuba	Southern Sierra Nevada
Tahoe-Sierra	Kern County
Mokelumne, Amador, Calaveras	Fremont Basin

One requirement of the IRWM program is that IRWM grants are required to show multiple benefits. IRWM-funded projects often work towards climate-change adaptation goals, even if they are not explicitly stated as the primary benefits of the project. Examples of such adaptations include implementing water conservation measures; incentivizing turf removal and native landscaping; investigating recycled water use; developing groundwater sustainability plans; evaluating and updating stormwater and flood control infrastructure; and restoring habitat in order to recover from previous disturbance and provide resilience for future climate change impacts.

The implementation of the Sustainable Groundwater Management Act implementation is also largely occurring at regional (and groundwater basin) levels. Stormwater and flood management have recently become high-priority at the state level; those entities wanting to apply for grant funding from the state for stormwater and flood management projects must now develop Stormwater Resources Plans for their jurisdictions or areas of interest. Water management and planning work implemented through these programs may not be motivated directly by climate change. Rather, local and regional water managers are responding to current challenges that their communities and livelihoods face, such as drought, variable precipitation, and flooding. Nonetheless, these efforts provide opportunities and incentives for incorporating climate-change adaptations that otherwise might be too expensive or contentious to pursue. One

of the most immediate and palatable avenues for preparing for climate change can be fixing the management and infrastructural problems that already plague the region and state. This will probably not be adequate to resist all climate-change vulnerabilities, but it is a necessary step towards that goal, should provide greater resilience, and may allow even more extreme transitions and realignments to be identified and undertaken.

Successful water-resource adaptations in the Sierra Nevada region are in the interests of the entire state.

It is in the interests of the millions of downstream, generally distant water users who are connected to upstream Sierra Nevada conditions by the state's many water conveyances to maintain and protect the Sierra Nevada headwaters. Sierra Nevada communities, many of which are rural and/or disadvantaged, are both the sources of some of California's most important water supplies and the recipient of the least amount of funding and other resources to help protect water. More education and outreach are needed for stakeholders and the public at local to state scales to better understand the vital role of Sierra Nevada water resources throughout the state as well as the challenges that climate change poses to continued availability of those resources.

3.3 Communities

Communities are being challenged by the changing climate, and their abilities to respond depend on severity of the challenge and the physical, social, financial, human, and cultural capital available to the community.

A changing climate with greater droughts and flood extremes, shifting temperature regimes, lengthening and enhanced fire seasons is challenging communities throughout the Sierra Nevada region. The ability of communities to respond to climate change impacts will vary based on the severity of conditions they face and their capacity to respond (Kusel 1996, Kusel et al. 2015). A community's capacity—the collective ability of residents in a community to respond to stressors including climate change impacts—comprises five components:

1. physical capital, which includes roads, water and sewer systems, and related infrastructure;
2. social capital, involving the willingness of residents to work toward community ends;
3. financial capital, the money available to address local needs;
4. human capital, which includes the skills, education, experience, and capabilities of the residents; and
5. cultural capital, the traditions, beliefs, and norms that help to organize communities and facilitate their continued well-being.

Many communities in the Sierra Nevada region are identified as disadvantaged and thus may be particularly challenged in terms of climate-change response and adaptation.

Many Sierra Nevada communities suffer from low socioeconomic conditions and have less capacity to respond to challenges like climate change. Community-level metrics are essential to clarify community conditions and their ability to respond to climate change; however, comprehensive community-level data are not readily available throughout the Sierra Nevada. The last comprehensive assessment of capacity and socioeconomic condition of Sierra Nevada communities was completed in 1996 for the Sierra Nevada Ecosystem Project, though later work has