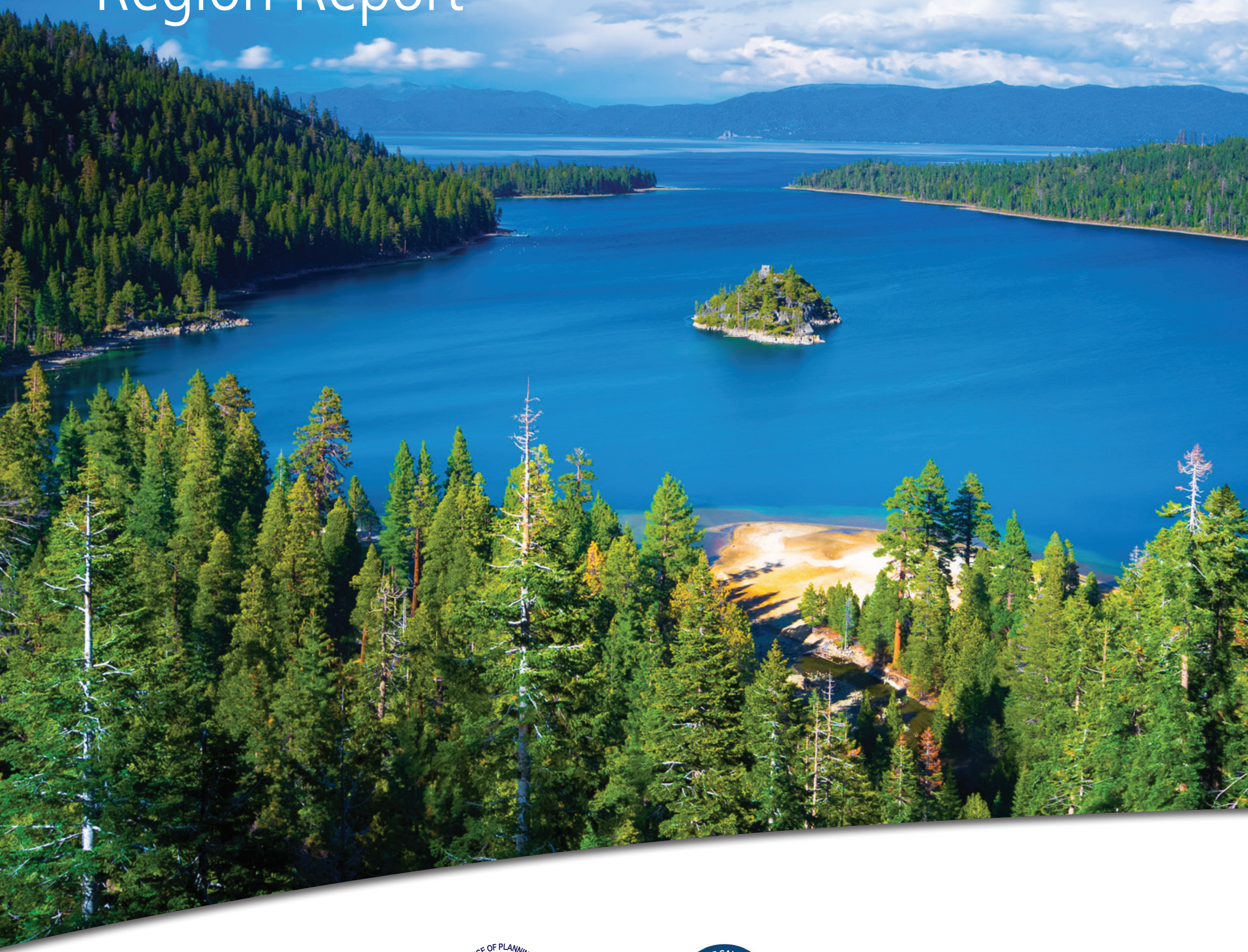
CALIFORNIA'S FOURTH
CLIMATE CHANGE
ASSESSMENT

Sierra Nevada Region Report

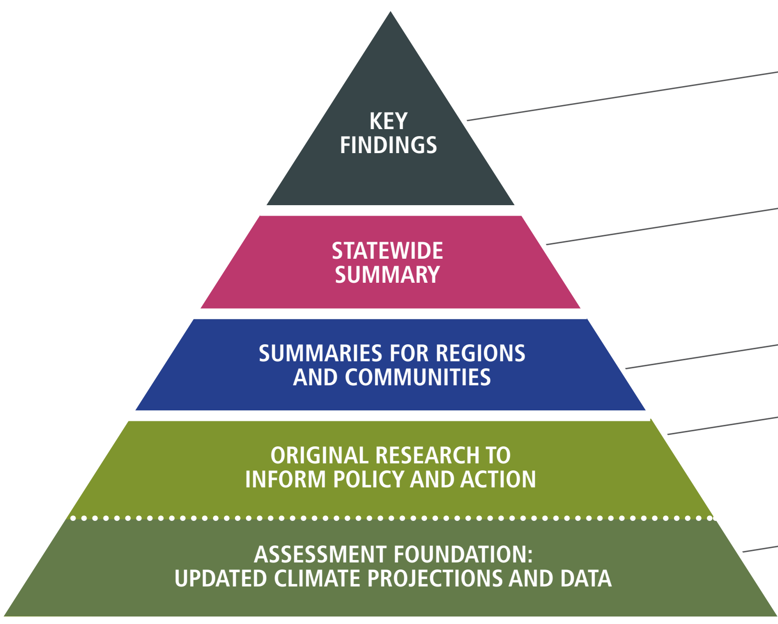


Coordinating Agencies:

Introduction to California's Fourth Climate Change Assessment

California is a global leader in using, investing in, and advancing research to set proactive climate change policy, and its Climate Change Assessments provide the scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. The Climate Change Assessments directly inform State policies, plans, programs, and guidance to promote effective and integrated action to safeguard California from climate change.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. This cutting-edge research initiative is comprised of a wide-ranging body of technical reports, including rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health. In addition, these technical reports have been distilled into summary reports and a brochure, allowing the public and decision-makers to easily access relevant findings from the Fourth Assessment.



- A concise summary of the Fourth Assessment's most important findings and conclusions.
- An in-depth report on how California's people, built environment, and ecosystems will be impacted by climate change and how we can proactively adapt, based on the Fourth Assessment's findings.
- Reports summarizing Fourth Assessment findings to provide a state of the science for nine regions, the ocean and coast, tribal communities, and climate justice in California.
- Academic research that provides robust and detailed results on resilience and vulnerability to climate change.
- A shared foundation of updated climate change projections, data and ecosystem models developed for use by Assessment authors to permit cross-comparability of results and ensure the findings consider a robust range of future climate conditions. These data are available to the public via Cal-Adapt.org.

All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor as well as, where applicable, appropriate representation of the practitioners and stakeholders to whom each report applies.

For the full suite of Fourth Assessment research products, please visit: www.ClimateAssessment.ca.gov

CALIFORNIA'S FOURTH
CLIMATE CHANGE
ASSESSMENT

Sierra Nevada Region

The Sierra Nevada Region Summary Report is part of a series of 12 assessments to support climate action by providing an overview of climate-related risks and adaptation strategies tailored to specific regions and themes. Produced as part of California's Fourth Climate Change Assessment as part of a pro bono initiative by leading climate experts, these summary reports translate the state of climate science into useful information for decision-makers and practitioners to catalyze action that will benefit regions, the ocean and coast, frontline communities, and tribal and indigenous communities.

The Sierra Nevada Region Summary Report presents an overview of climate science, specific strategies to adapt to climate impacts, and key research gaps needed to spur additional progress on safeguarding the Sierra Nevada Region from climate change.

CALIFORNIA'S FOURTH
CLIMATE CHANGE
ASSESSMENT

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Executive Summary

The Sierra Nevada region is critical to the environment and economy of California. Its places and peoples provide essential natural resources including fresh water, clean power, working lands, and famous wilderness. The region encompasses tremendous geographical, climatological, and ecological diversity that spans majestic mountains to deep desert basins. The climate consists of cool, wet winters and warm, dry summers with large differences due to latitude (e.g., the southern Sierra is snowier than northern Sierra) and topography (e.g., the Westside is wetter than the Eastside). Variability is another notable feature of the climate with the region experiencing some of the largest year-to-year climatic fluctuations in the United States. Herein we summarize our assessment of climate-change vulnerabilities and adaptation actions in the region.

Projected climate changes: Climate change is already underway in the Sierra Nevada region, affecting heat and precipitation extremes, with long-term warming trends, declining snowpacks, and changes in streamflow timing. These ongoing trends foreshadow larger changes to come. By the end of the 21st century, temperatures in the Sierra Nevada are projected to warm by 6 to 9°F on average, enough to raise the transition from rain to snow during a storm by about 1,500 to 3,000 feet. In contrast, future precipitation is predicted to vary less than temperature; long-term changes may be no more than ±10-15% of current totals. However, precipitation extremes (both as deluge and drought) are expected to increase markedly under climate change. These climatic changes will depend on and reflect many factors, including elevation within the mountain range, with quicker warming trends and precipitation changes at highest elevations.

As a result of projected warming, Sierra Nevada snowpacks will very likely be eradicated below about 6,000 feet elevation and will be much reduced by more than 60% across nearly all of the range. Notably, though, recent studies suggest that even these snowpack-loss projections may be underestimates, due to feedback loops with warming trends causing snow cover losses, and snow cover losses resulting in warmer land surfaces and thus enhanced warming trends in turn.

The loss of snowpack will combine to dry soils 15% to 40% below historical norms, depending on elevations. The result will be reduced soil and vegetation moisture; changes in rivers and lakes; and ultimately stresses on flora and fauna. Loss of snowpack and overall drying will lead to increased winter streamflows and floods, and to (largely compensating) reductions in spring and summer streamflows.

Framework for adaptation: In considering several major vulnerabilities and arenas for climate-change adaptation in the Sierra Nevada, two basic framings provided useful organizing principles. First, a recommended strategy for developing adaptation options includes (1) understanding historical trends, (2) identifying vulnerabilities, (3) developing strategies, and (4) monitoring results. This report discusses ecosystems and wildlife, water resources, and human communities with these steps in mind. Second, not all adaptations seek to completely avoid climate-change impacts. Four categories of adaptation, in order of increasing intervention, are efforts to support (1) resistance (trying to ward off climate-change impacts), (2) resilience (increasing the capacity of systems to absorb and bounce back from climate changes), orderly response (assisting transitions to avoid at least the most undesired outcomes), and realignment (facilitating major transitions to the most desirable new conditions) to the new climate-changed environment that is coming.

Ecosystems and biodiversity: Climate is a major driver of ecosystem composition, structure, and dynamics. Even optimistic projections of warming indicate a future with more wildfire, more drought stress, and lower carbon storage in the Sierra Nevada. High elevation forests and old-growth mixed conifer forests are the most vulnerable to projected changes in climate and wildfire. Development pressures combined with warming are likely to result in oak-woodland declines, whereas meadows are particularly vulnerable to disruptions of local hydrology.

Climate variations and changes can directly impact physiological processes in sensitive species. Observed trends to date in the distributions of mammals, butterflies, and birds demonstrate that future range shifts are likely. Climate-driven shifts in species distributions will disrupt many natural communities, yielding new assemblages with unknown and challenging ecological interactions. Vulnerability to climate change is widespread among wildlife but old-growth forest species are likely the most sensitive.

A wide-ranging portfolio of adaptation options is available to reduce the vulnerability of Sierra Nevada forests, woodlands, and wildlife to climate change. Relatively low-impact means exist to improve resistance and resilience in montane meadows, while re-alignment involves more intrusive approaches. Adaptation strategies for vulnerable wildlife species should emphasize approaches that protect climate refugia and maintain migration corridors.

Water Resources: Climate-change impacts on Sierra Nevada water resources will be important for both local communities and for millions of downstream water users throughout the state. Predicted trends of temperature and precipitation will directly influence the regional water cycle, including uncertain but potentially large changes in natural and societal water demands.

Snowpack losses are already underway in the Sierra Nevada, and associated changes in snowmelt timing and streamflow availability will challenge some local to state-scale water management systems. Water resource management most often comes down to drought management in the Sierra Nevada; climate change will only aggravate the problem. Flood risks are projected to increase under climate change, stressing some existing water (and community) infrastructures. The vulnerability of groundwater supplies is less well understood but is expected to vary from area to area. For example, groundwater plays particularly important roles in the volcanic-rock aquifers of the northernmost Sierra Nevada and the Modoc Plateau. Climate change may impact the region's water quality in a large number of ways; all are still quite uncertain. Because Sierra Nevada populations are predominately rural and, in many places, disadvantaged, local water-resource management is frequently limited by lack of human and financial resources.

Water resources management for 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. Increased surface-water storage in new or expanded reservoirs is frequently discussed as an adaptation option, but remains a source of friction between water purveyors (and flood managers), local communities, and conservation organizations. Better coordination of surface-water and groundwater supplies should be important considerations in discussions of new storage options. Integrated Regional Water Management and the Sustainable Groundwater Management Act provide two avenues for developing and implementing needed adaptations. Successful water-resource adaptations in the Sierra Nevada region are in the interests of the entire state.

Communities: Climate change threatens to exceed the capacity of some communities in the Sierra Nevada region to respond given the current availability of physical, social, financial, human, and cultural capital. Many communities in the Sierra Nevada region are identified as disadvantaged and thus may be particularly limited in terms of climate-change adaptation.

The economies of most Sierra Nevada communities are dependent on the natural resources (forests, agriculture, and tourism) that surround them. The many communities that rely on the forest products industry were hit particularly hard by the Great Recession of 2008-2009. Some of the region's communities are economically and culturally tied to agriculture and thus need stable water supplies and reliable weather. The fates of tourism-dependent communities are linked to the snowpack, stream and lake conditions, and forest health.

Water uses and sources differ from community to community. Thus, the climate related threats to water quantity and quality will vary. Capacities to address these challenges also differ from community to community, and are limited in many of the more disadvantaged rural communities.

Combined effects of drought, decline in forest health, and wildfire—all of which climate change will exacerbate—threaten the life and property of communities, especially in the wildland-urban interface throughout the region. Inadequate capacity to restore forest health (including more natural wildfire intensities and extents) limits land-management options for preparing for climate change. Inadequate capacity (e.g., at remaining mills) to safely and economically remove and use byproducts (wood and other biomaterials) of forest restoration is a primary challenge to restoration effort throughout the region.

Increased heat and precipitation extremes are expected to impact the region's transportation and other infrastructures. Hydroelectric generation may be reduced by climate change, but electricity demands within the region may be more shielded (by overall cool climes) in the mountainous parts of the region.

Climate change imperils the public health and well-being. Age, disability, and geographic/social isolation may aggravate climate-change challenges and limit responses by the region's population. Health impacts from heat waves and poor air quality are especially likely to be enhanced by climate change.

Among the most encouraging signs regarding adaptation to a changing climate are the rise of collaborative groups and, more recently, a new openness to these groups from land management agencies. New policy and programmatic innovations are providing tools and authorities to accelerate forest-management efforts, including stewardship authorities and community-responsive contracts. Stakeholder collaborations and community-based organizations are developing in the region to improve the capacity for landscape-scale forest management and restoration that crosses land ownerships. Communities are speaking up to agencies for triple-bottom line prioritization that balances social, economic, and ecological goals. Ultimately, ecosystem health, economic health, community health, and human health are interlinked in the context of climate change. Thus, integrated strategies (like IRWM programs) and the rebuilding of community adaptation capacities are critical to climate change adaptation in the region.

Adaptation in the Region: Agencies, communities, and other organizations throughout the region are already at work on a wide variety of adaptive measures that are improving the condition of present-day landscapes and communities as well as providing improved prospects in the face of coming climate changes. Current examples of efforts to adapt include:

ECOSYSTEMS AND BIODIVERSITY:

- The Sierra Nevada Watershed Improvement Program led by the Sierra Nevada Conservancy and U.S. Forest Service, aiming to restore the health of primary Sierra Nevada watersheds through increased investment and needed policy changes
- A growing number of teams working to improve forest health and to reestablish wildfire to its proper place in the region's ecosystems, including the Fire MOU Partnership, several major activities in the Lake Tahoe Basin, several Collaborative Forest Landscape Restoration Projects, and local programs like the French Meadows Forest Resilience Project.
- Meadow-restoration efforts, including those of the Sierra Meadows Partnership and the Native Youth Conservation Corps.

WATER RESOURCES:

- Fifteen Integrated Regional Water Management regions, and planning efforts spawned by the Sustainable Groundwater Management Act.
- More local initiatives like the Lake Almanor Watershed Group and South Lassen Watersheds Group that are addressing water quality and quantity, and forest health issues, in their areas.

COMMUNITIES:

- Tribal efforts to enhance water, wildfire, and food security, and to prepare for climate change on their lands and surroundings.
- Community collaborative efforts by coalitions like Amador-Calaveras Consensus Group and California Healthy Impact Product Solutions groups.
- Climate-smart land-preservation activities like those promoted by Point Blue Conservation Science and the California Council of Land Trusts.
- Climate-smart development activities like those recommended by the Sierra Nevada Alliance and Sierra Green Building Association.

Climate change is going to bring major changes to the region's and state's living and water resources and communities. These kinds of adaptation initiatives are needed to put the region on the firmer footing it will need to forestall or avoid the most deleterious of the coming changes.

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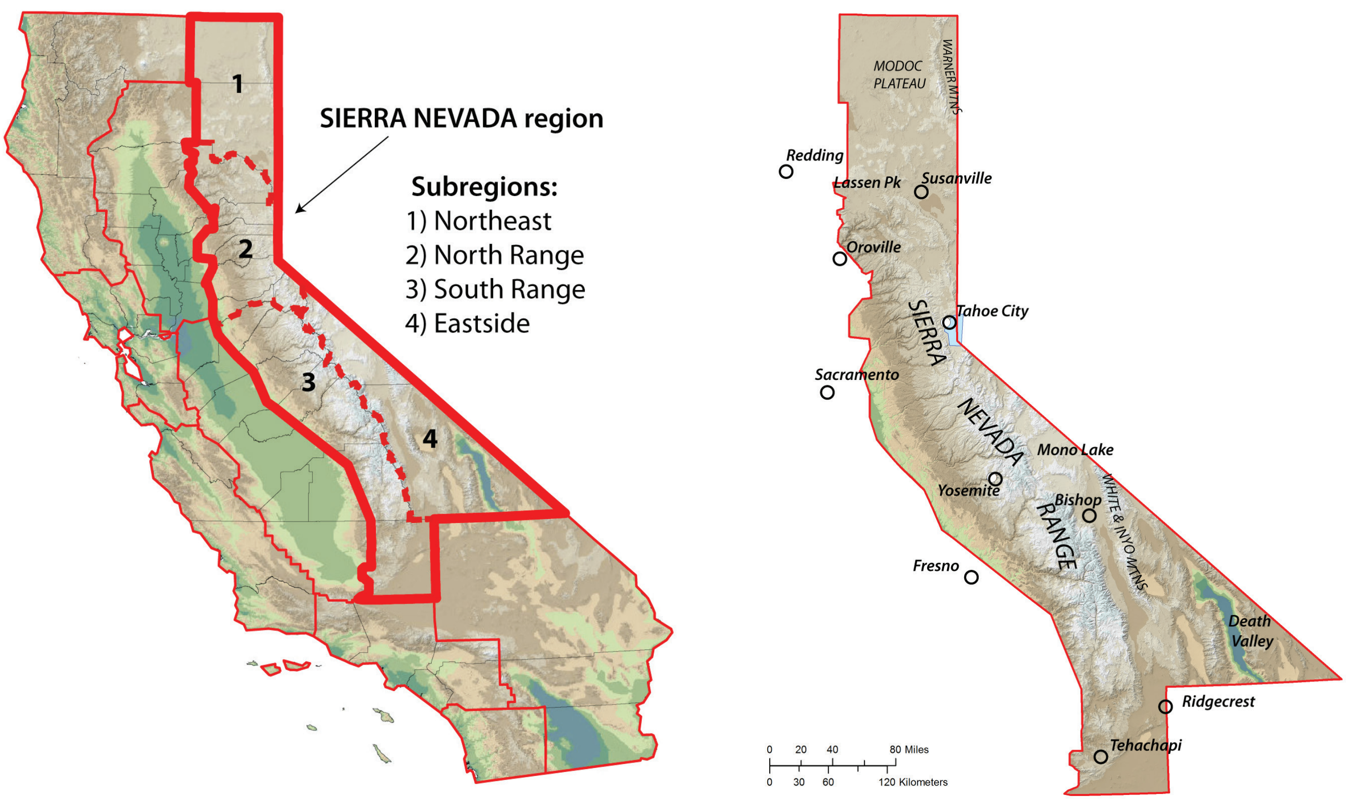
1: Introduction

The Sierra Nevada region is the backbone of water, electrical power, environmental, forest, and other resources in California.

The Sierra Nevada region (Fig. 1.1) forms the topographic and resource-based backbone of the State of California (Storer and Lukas 2004). The Sierra Nevada itself (about half of the region) produces an average of about 26 million acre-feet of annual streamflow that flows west into the Central Valley with another 2 million acre-feet flowing east into the rain-shadowed desert valleys. Hydroelectric power generated from Sierra Nevada rivers amounts to half of all hydroelectrical production in the State, about 15% of all in-state power generation, and 9% of all electrical power used in the State. Present estimates of the amount of subsurface (groundwater) flow from the range to surrounding valleys amount to about 0.5 million acre-feet to the Central Valley (Faunt 2009) and 0.1 million acre-feet to the east. The Sierra Nevada region contains most of the forests and high-elevation landscapes and habitats in the State, and provides abundant recreational and economic opportunities for Californians. Roughly a million people live in the Sierra Nevada region.

FIGURE 1.1



Location of Sierra Nevada region, subregions (upper), and some locales (lower) within the region for use in orienting one's self.

BOX 1. WILDFIRE IN THE SIERRA NEVADA REGION

Fire is a major feature of the ecology of most Sierra Nevada ecosystems (Keeley and Safford 2016). However fire's impact varies by virtue of the species it touches, their adaptations, and the environmental setting at the time of burning, both of which can be affected—directly and indirectly—by humans (Mallek et al. 2013, Steel et al. 2015). While fire has always been present in California (Keeley and Safford 2016), its role has been notably shaped and reshaped by human cultural practices (Taylor et al. 2016).

California's indigenous tribes used fire for a variety of purposes, altering the natural fire regime and reflecting a deep understanding of fire as a natural process and a tool (Anderson 2005). In Sierra Nevada yellow pine forests (dominated by ponderosa and Jeffrey pine), tribes used fire to eliminate brush and promote food stuffs (Anderson 1999). Burning practices altered forest structure and maintained vegetation in early successional stages along the lower slopes on both sides of the Sierra Nevada (Kilgore 1973). By 1860, burning by indigenous people in California was sharply curtailed (Kilgore 1973) as tribal peoples were extirpated and their land taken by Euro-American emigrants (Lindsay 2012).

Euro-American settlement of the Sierra Nevada in the mid-19th century promoted an abrupt shift in fire regimes. The immediate increase in resource use (e.g., for timber harvests, grazing, mining, and water diversion) and the subsequent imposition of comprehensive fire exclusion during the first half of the 20th century caused widespread changes in ecosystems. Forests were particularly affected in low- to middle-elevation zones where the lack of recurring low- and moderate-intensity fires that characterized the fire regime for millennia led to a buildup and increase of continuity of forest fuels (Anderson 2006, Collins et al. 2011). At the same time, population growth and development have increased human presence in fire-prone ecosystems, leading to an increase in ignitions near the wildland-urban interface (Hammer et al. 2007, Syphard et al. 2007). Today, yellow pine and mixed conifer forests are at high risk of large, uncharacteristically severe wildfires that can impose long-term ecosystem damage (Miller et al. 2009, Safford and Stevens 2017).

In addition to increased fire risk, altered fire regimes can act as stressors on various elements of the ecosystem. In yellow pine and mixed conifer forests, plant species evolved with relatively frequent fires, and their life histories, reproduction and growth are tied to the fire regime. Thus, changed fire regimes may have consequences for species persistence (Webster and Halpern 2010, Keeley 2010). Overall ecosystem health involves complex interactions among agents of disturbance, including fire, drought, insects, and diseases. Changes in one agent can accentuate risks from others. For example, fire suppression in Sierra Nevada forests in the last century has led to increases in tree density, declines in the abundance of large trees, and shifts in composition toward more fire- and drought-intolerant species (Collins et al. 2011, Dolanc et al. 2014, Scholl and Taylor 2010). The resulting denser and more homogeneous forests are at greater risk from drought, insect outbreaks and disease, not to mention greater risk of high severity fire (Stephens et al. 2018). The spread of invasive species can also be facilitated by severe wildfires (Lambert et al. 2010). Ultimately, wildlife, water quality, and air resources are all tied to the spatial and temporal patterns of fires.

Fire is a pervasive and recurring process across the region. Thus, it is a pervasive and recurring theme in this report. We first describe fire's roles and risks for natural processes and ecosystems, and then for human communities and well being, in the face of climate change.

This is a region of tremendous geographical, climatological, and ecological diversity, ranging from major mountains to deep desert basins.

The Sierra Nevada mountain range extends some 440 miles from north to south, spanning seven degrees of latitude and comprising about 18,000 square miles. Elevations along the ridgeline of the range are at their highest in the southern Sierra Nevada—with Mount Whitney as the highest point in the conterminous US at 14,505 feet above sea level—and then drop gradually to the north; the highest peaks north of Lake Tahoe are around 8,000 feet in elevation. Other high mountains in the Sierra Nevada region include the Warner Mountains in northeastern California (eastern edge of the Modoc Plateau, highest elevations nearly 10,000 feet), and the White and Inyo Mountains east of the southern Sierra Nevada, where the highest peaks are between 12,000 and 14,200 feet. The Sierra Nevada region also extends down to desert basins adjacent to, and along the Nevada border, including Death Valley, the lowest point in North America. Throughout the ranges, broad areas are high and cool enough so that most of the State's snowpacks are formed here each winter, mostly in the mountains. These snowpacks comprise a seasonally varying natural reservoir that holds water equal to—on average in spring—about two-thirds of the average overall volume of water stored in the State's man-made reservoirs. Those infrastructures were designed almost without exception to rely on the seasonal storage of about 42% of all the water moving through the State's water systems in snowpack each winter and spring. That water is then released as snowmelt months later to rivers, reservoirs, and downstream uses. Despite its role as "California's reservoir", the Sierra Nevada region is largely an arid, fire-prone landscape. Thus, wildfire is a major driver of its ecology and a major threat to its infrastructure (Box 1).

THIS REPORT PROVIDES IMPORTANT INFORMATION ABOUT KEY CLIMATE-CHANGE VULNERABILITIES AND ADAPTATIONS.

In this assessment, the Sierra Nevada region comprises the Sierra Nevada Range itself, plus Lassen and Modoc counties to the northeast (called the Northeastern subregion here) and Mono, Inyo, and the eastern half of Kern counties to the southeast (the Eastside subregion). The region encompasses part or all of some 27 counties. In a broad sense, ecosystems in the region grade from oak savannas and chaparral at lower elevations to the west, to mixed evergreen and mixed conifer forests at middle elevations, to red fir and subalpine forests and then rocks and scattered alpine vegetation formations (e.g., fell fields and meadows) above the tree line. Descending the Sierra Nevada to the east, pine-dominated forests give way to steppe and cold-desert ecosystems dominated by sagebrush and drought- and saline-tolerant shrubs. The Modoc Plateau and landscapes east of the Sierra Nevada crest but north of Lake Tahoe support scattered conifer forests and large expanses of pinyon pine, juniper, and sagebrush. The White and Inyo Mountains are high elevation desert landscapes, with minimal forest and vegetation cover. All of these landscapes have their own individual vulnerabilities to climate change, as do the human populations that live and work in or near them.

Most of the working lands in the Sierra Nevada region are forest and rangeland. Urban areas and agriculture make-up less than 3% of the area while forests, shrublands, and grasslands account for 90%. By area, the most common plant associations include desert scrub, sagebrush, and Sierran mixed conifer forest, but there are important distinctions among the four sub-regions. Forests are the dominant vegetation in Northern and Southern Range while steppe shrublands are the most abundant vegetation type in the Northeastern and Eastside subregions. Conifer forests account for 60% of the land in the Northern Range compared to 35% in the Southern Range. On the Eastside, 76% of the landscape is desert scrub and sagebrush; in this subregion, conifer forests make up only 11% of the vegetation. The Northeastern subregion, too, is mostly populated by shrublands (nearly half), but conifer forests are still common (35%). In this subregion, grasslands and agriculture together cover 12% of the landscape, a significant minority (FRAP Vegetation, 2015).

In addition to this environmental diversity, the region hosts a great diversity of land-use history, ownership, and socio-economic statuses. This report aims to provide accessible and important information at a scale relevant for decision makers to support policies and programs to improve resistance, build resilience, assist response, and promote realignment to climate change in California's human and natural communities, natural resources, and infrastructure, to provide a basis for broad public support for climate science and adaptation action in the region and across the State, and to share California's approach to climate-change adaptations with other jurisdictions in the US and abroad. Our primary audiences are decision makers, planners, community members, and other stakeholders both within the Sierra Nevada region and statewide. To accomplish these aims for this audience, the next section will provide an overview of the region's historical climate and the latest projections of 21st century climate in the Sierra Nevada region, followed by sections that describe key issues, vulnerabilities, and adaptation options for the region's forests, water resources, economies, and communities, and a few other concerns, followed by a summary of needs and opportunities in the region. Pale-green text boxes describing various adaptation efforts underway in the region are interspersed throughout.

2: Sierra Nevada Climate and Climate Projections

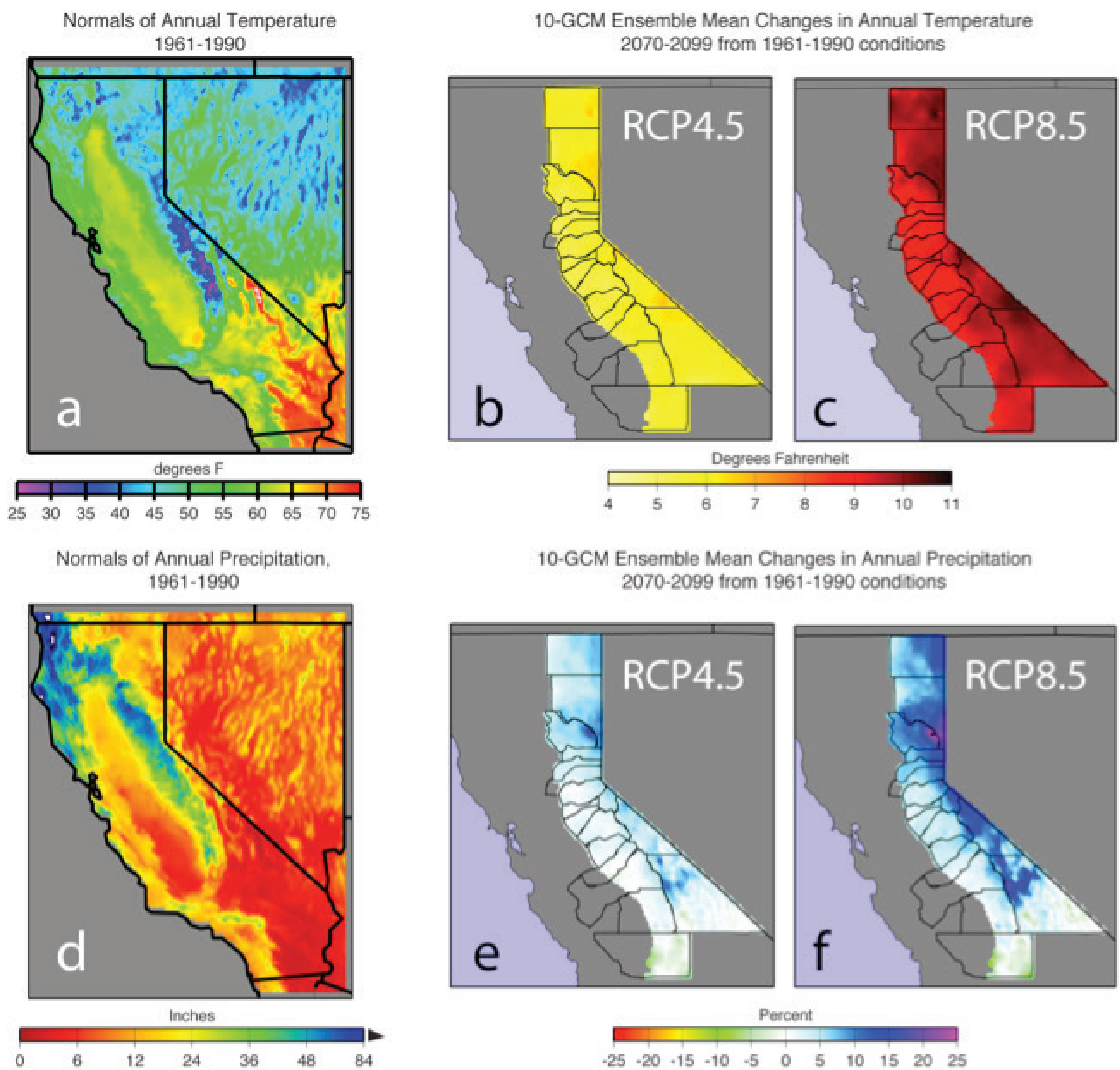
2.1 Historical Climate

The Sierra Nevada region experiences cool, wet winters and warm, dry summers with large climatic differences due to the topography (e.g., southern Sierra is snowier than northern Sierra) and with some of the largest year-to-year climatic fluctuations in the United States.

The climate of most of the Sierra Nevada region is mostly Mediterranean in character with cool, wet winters followed by warm to hot, dry summers (Dettinger et al. 2016; Polade et al. 2017). East of the Sierra Nevada crest there is a strong Great Basin influence, with colder winters and higher probability of summertime rainfall. The western slopes of the mountain range receive moisture and warmth mostly from prevailing westerly winds off the North Pacific Ocean, with many of the largest (cool-season) storms arriving as atmospheric river storms (moisture-laden jets in the lower atmosphere that release significant amounts of precipitation as they rise up and over the mountains). The eastern slopes of the range and the high deserts east and north of the range receive winter precipitation mostly as spillover from the atmospheric rivers on the western slopes, but also partake of the Great Basin climate including wintertime "inside sliders" (storms that arrive on the east side of the range from the northwest) and some summertime monsoon precipitation. Precipitation is enhanced in the Sierra Nevada, as storms pass up (in elevation) and over the range from the west, cooling as they do, with moisture condensing into clouds and precipitation in the process yielding extra precipitation on the upwind sides of the range. As a result, the mountainous parts of the region are much wetter than immediately surrounding areas, both within and beyond the region. Elevations between 5000-6000 feet on the west slope of the Sierra Nevada tend to be the wettest in the region. Because storms are much depleted by their passage up and over the Sierra Nevada, the desert areas to the east are severely rain-shadowed and much drier (Fig. 2.1d). The relatively high elevations of the mountains and deserts ensure that the Sierra Nevada region is generally cooler than adjacent regions (Fig. 2.1a). Because the southern Sierra Nevada is mostly higher than the northern Sierra Nevada, temperatures are cooler and precipitation is snowier than in the northern part of the range. However, because the northern parts of the range are more directly in the path of strong North Pacific storms (especially atmospheric rivers; Rutz et al. 2014), the northern Sierra Nevada is generally wetter than the southern part of the range (Fig. 2.1d).

California in general is remarkable within the Nation for its highly variable climate. In the Sierra Nevada region, annual precipitation totals historically have fluctuated between about 50% to 200% normal from year to year, whereas in most of the rest of the country fluctuations are more typically only plus or minus 10 to 20% (Dettinger et al. 2011). Because enhancement of precipitation over the Sierra Nevada can fluctuate dramatically from year to year and because precipitation totals are especially sensitive to how many strong storms arrive in any given winter, precipitation totals vary widely within the region. For example, during the recent 2012-2016 drought, the western foothills of the range (and adjacent Central Valley) received an extra half a normal year's worth of precipitation compared to the high parts of the range. Temperature fluctuations in the range are large but are somewhat buffered (reduced) compared to areas farther inland by proximity to the Pacific Ocean, which acts as a globe-spanning thermal mass that absorbs and buffers both seasonal and year-to-year temperature variations. At the same time, the Sierra Nevada is in the path of climatic fluctuations emanating from the Pacific Ocean, on a wide range of times scales from weeks to decades, the best known of which is El Nino (e.g., Lee et al. 2018). All of these Pacific climate variations contribute to the region's temperature and precipitation variability.

FIGURE 2.1



a) and d), historical normal annual-average temperature and precipitation; b), c), e), f), average changes in temperature and precipitation in the region by 2070-2099, as projected by ten different global-climate models in response to moderated RCP4.5 greenhouse-gas emissions (b, e) and accelerating RCP8.5 greenhouse-gas emissions (c, f). County boundaries indicated in black.

2.2 Temperature & Precipitation Change

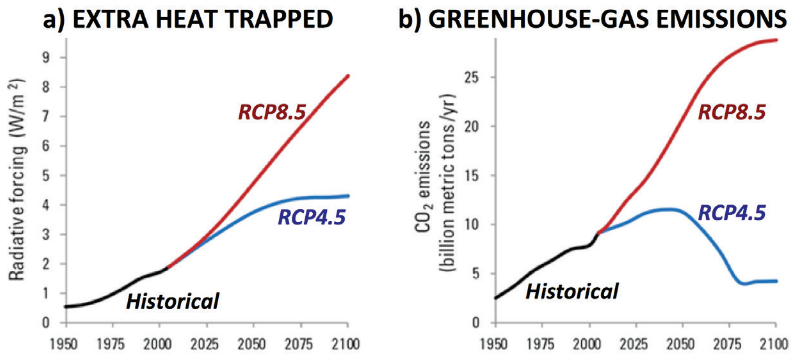
Climate changes are already underway in the Sierra Nevada region, affecting heat and precipitation extremes, with long-term warming trends, declining snowpacks, and changes in streamflow timing that presage much larger changes to come.

Artificially high concentrations of greenhouse gases have been accumulating in the global atmosphere since at least the Industrial Revolution, and now are accumulating at dangerously fast rates (Bereiter et al. 2015; Franco et al., in review). These gases—including carbon dioxide, methane, and even water vapor—are called "greenhouse gases" because they act like the glass in a greenhouse's walls to trap extra heat within the planetary system (heat that enters as sunshine and then is absorbed by atmosphere or land and ocean surfaces), raising temperatures of the oceans, land surfaces, and the atmosphere, in the process changing many aspects of climates around the planet. Careful evaluations of historical records and comparisons to simulations by climate models responding to the historical increases in greenhouse-gas concentrations have rigorously shown that several recent trends seen in the major mountain ranges of the western US, including the mountains of the Sierra Nevada region, are early symptoms of contemporary climate change (Barnett et al. 2008). These trends have been occurring since about 1950, in response to increasing greenhouse-gas concentrations in the atmosphere. They include warming of nighttime temperatures, declines in the fraction of precipitation that falls as snow rather than rain, and changes in the timing of snowfed streamflow (Barnett et al 2008). These trends are projected to continue, by all modern climate models, and to accelerate during coming decades. They will also be increasingly joined by trends in daytime temperature increases, precipitation changes, and changes in precipitation extremes as well as by trends in snow, soil and vegetation dryness, streamflow amounts, air quality, and other climate impacts that are as-yet still largely obscured by natural fluctuations.

By end of century, temperatures in the Sierra Nevada are projected to warm by 6 to 10ºF on average, enough to raise the divide between rain and snow during a storm by about 1500 to 3000 feet.

Climate projections in this report are responses by collections of climate models to two plausible greenhouse futures, arising from different ways that humans might manage future greenhouse-gas emissions: One future — labeled **RCP4.5, for a "Radiative Concentration Pathway that traps 4.5 W/m² of extra heat by 2100"**—assumes that extra heat trapped by greenhouse-gases that humans have introduced to the global atmosphere grows until century, slowing rapidly thereafter to stabilize later in the century (figure 2.2a). This future would result if we begin reductions in emissions by about 2040, and stabilize emissions at low levels by about 2080 (figure 2.2b). The other future--labeled **RCP8.5, for Radiative Concentration Pathway that traps 8.5 W/m² of extra heat by 2100**—assumes, on the contrary, that greenhouse-gas concentrations and extra heat continue to increase throughout the century (figure 2.2a). This future would result from greenhouse-gas emissions that aren't stabilized until about 2100 and never reduced (figure 2.2b). In response to these two futures, different climate models yield different results. Because of this, modern climate projections are best interpreted in terms of the extent to which many models (so-called ensembles of models) agree about likely climate changes in climate. In this report, most projections are presented as results from ten different models responding to the two futures shown in Fig. 2.2, provided by Cayan et al. (2018).

FIGURE 2.2



a) Extra heat trapped in the earth system (atmosphere, oceans, and land surface) by anthropogenic emissions of greenhouse gases, historically and under two assumptions about future emissions, and b) rates of anthropogenic greenhouse-gas emissions that would result in the extra heat shown in panel a).

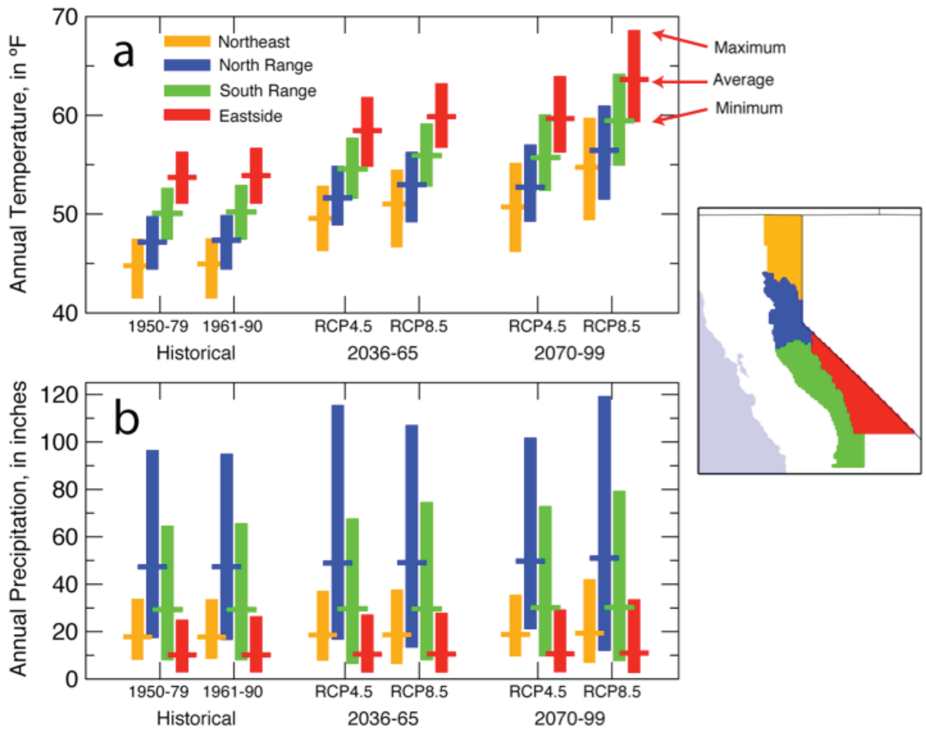
Figs. 2.1b-c and 2.1e-f show the average of projected temperature and precipitation changes from just such an ensemble. By the last 30 years of this century, the average projected warming in the Sierra Nevada region by ten climate models responding to ever-accelerating greenhouse-concentrations (Fig. 2.1c) is +9ºF in the northern Sierra Nevada, 9.2ºF in the southern Sierra Nevada, and 9.8ºF northeast and southeast of the range (Figs. 2.1b-c). Under an assumption that greenhouse-gas emissions and concentrations will level off by roughly midcentury (Fig. 2.1b), the projected warming is 3 to 4ºF less. These temperature increases would be enough to raise the divide between rain and snow during a storm by about 1500 to 3000 feet. All of the climate models project warming but the year-to-year temperatures in individual simulations, and even the magnitude of long-term trends, differ from model to model. Fig. 2.3a shows the averages of all of the projected annual temperatures from the ten climate models, and the full range of scatter around those averages, for the four subregions and for four 30-year periods. The projected amounts of warming will take the subregions well beyond the historical range of temperatures, and soon (e.g., by about 2060), the coolest years among any of the projections shown will be warmer than nearly all years in the pre-1980s period in

Fig. 2.3. By the end of the century, nearly all years from any of the models under the RCP8.5 assumption of ever-increasing greenhouse-gas concentrations will be warmer than average years if greenhouse-gas concentrations can be reined in by midcentury (RCP4.5).

Future precipitation totals are less certain and long-term changes may not be more than about ±10-15%, but precipitation extremes (both as deluge and drought) are projected to increase markedly and simultaneously.

Projections of future precipitation totals are much more scattered and projected trends are relatively small (Fig. 2.3b). The average of precipitation projections from the ten climate models ranges only between about -5% to +10% depending on location within the Sierra Nevada region (Figs. 2.1e-f). Whatever precipitation trend might be embedded in the projections (summarized in Fig. 2.3b) is small compared to the wide year-to-year range of precipitation that already naturally characterizes California's climate. On the whole, in the current ensemble of projections, there may be a small tendency (about 10%) towards a wetter Sierra Nevada region, but in fact the projected precipitation trends remain small and uncertain. Most of the changes evident in these figures occurs in the winter-spring wet season that provides the large majority of the region's totals. However, particularly in the Eastside subregion (fig. 1.1a), Meixner et al. (2016) report projections of changes in summertime monsoon precipitation, including overall delays in timing of monsoon precipitation.

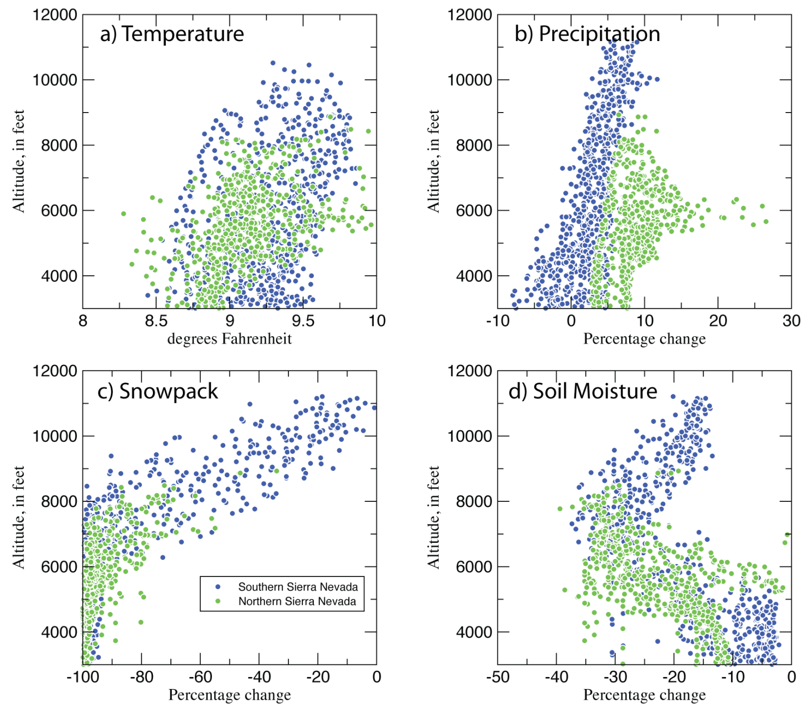
FIGURE 2.3



Thirty-year averages of projections of historical-era and future annual-averages of annual average temperatures (a) and annual precipitation totals (b) over four subregions indicated in inset map, from ten different climate models under two different assumptions regarding future greenhouse-gas concentrations, with ever-increasing RCP8.5 concentrations and moderating RCP4.5 concentrations.

Note however that Fig. 2.3b portrays a notable tendency for the range of precipitation totals to increase in the future to levels beyond those simulated (and observed) in the historical era. This change is common to nearly all climate models assessed and is a reflection of a tendency for projected changes in Sierra Nevada precipitation extremes (on a variety of time scales) to increase as a part of climate change in the 21st century. Nearly everywhere in the Sierra Nevada, the amount of precipitation from the largest storms—e.g., maximum-annual 3-day precipitation totals (CCTAG 2015) and atmospheric rivers (Espinoza et al. 2018) — is projected to increase between by 5-30% compared to historical norms, depending on how greenhouse-gas emissions evolve in coming decades. Polade et al. (2017) showed that projected annual-precipitation changes in California (including the Sierra Nevada) reflect the combination of increased numbers of dry days and increases in the largest storms, with much smaller changes in storms between those two extremes. Dettinger (2016) showed that projected changes in annual precipitation reflect the changing balance between contributions from those largest storms and all remaining storms. On longer time scales, Ault et al. (2014) and Cook et al. (2015) showed that these climate projections include enhanced odds of multi-year to multi-decade droughts over the entire Southwest. Recently, Swain et al. (2018) showed that—in a single climate model under RCP8.5 emissions—extremes at the wettest end of the spectrum (e.g., 200-year storm sequences) also increase in likelihood under climate change, as do likelihoods of rapid flip-flops between extreme drought and extreme wet years. Overall then, current projections of future precipitation reflect small changes in average precipitation (of uncertain sign) that nonetheless include a consensus projection of more dry days punctuated by increased precipitation intensities when precipitation does come. That is, dry conditions with occasional larger storms, or little net change but more extreme conditions throughout.

FIGURE 2.4

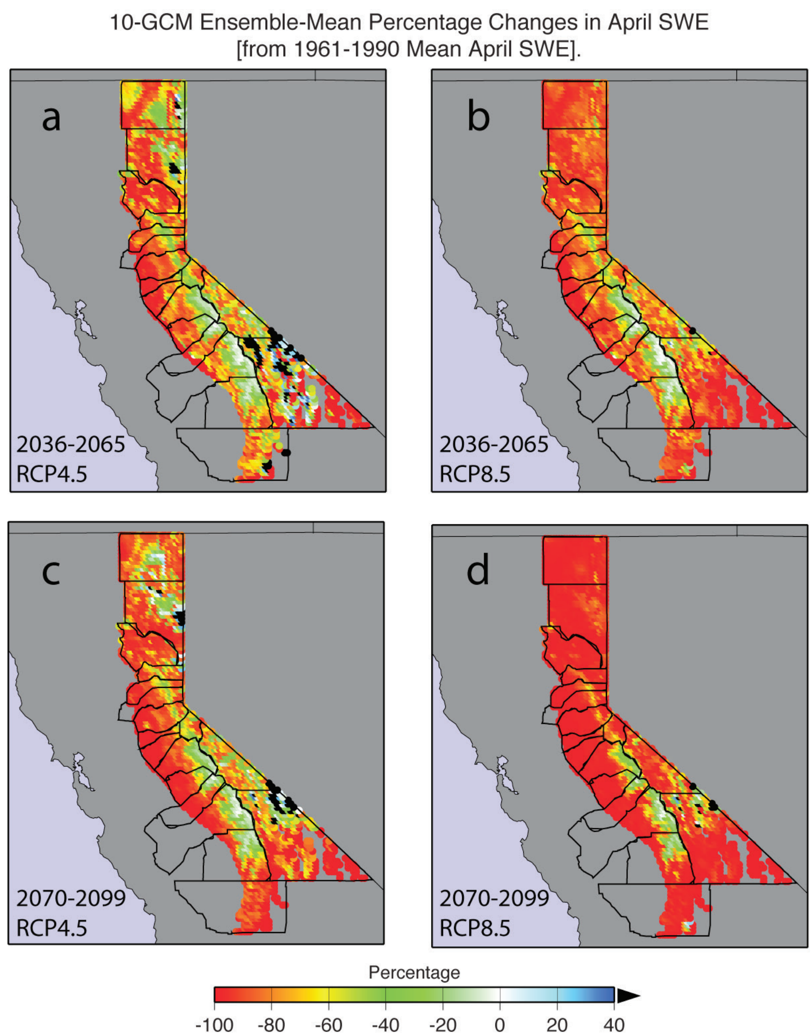


Average projected changes, by 2070-2099, in (a) annual temperatures, (b) annual precipitation, (c) April snow-water equivalents, and (d) June-September soil moisture as functions of elevation and subregion in the mountain range, from the 10-model ensemble of climate models responding to accelerating RCP8.5 greenhouse-gas emissions shown in Fig. 2.1c, 2.1f, 2.5d, and 2.7e, as degrees of warming (a) or percentage changes from 1961-1990 average conditions.

These climatic changes will depend on and reflect many factors, including elevation within the mountain range, with quicker warming trends and precipitation changes at highest elevations.

Besides maps and large-scale averages, another way to orient ourselves and characterize climate in the Sierra Nevada is by elevation. Figs. 2.4a-b show the averages of projected annual-temperature and annual-precipitation changes in the Northern and Southern Range subregions plotted against elevation. Warming generally increases from about +9°F at 3,000-ft elevations to +9.5°F at 10,000 feet, in accordance with trends of enhanced warming at higher elevations that have already been detected globally (e.g., Wang et al. 2014). Average projected precipitation rates mostly increase (as in Fig. 2.1f) throughout the range, with more increase in the Northern Range and with modest tendencies for greater increases at the higher elevations. (The large increases at 6,000 feet in the Northern Range correspond to the purple area in Fig. 2.1f, an odd percentage-increase in the historically small precipitation rates around the Honey Lake-Susanville (Fig. 1.1) area at the northeastern end of the range).

FIGURE 2.5



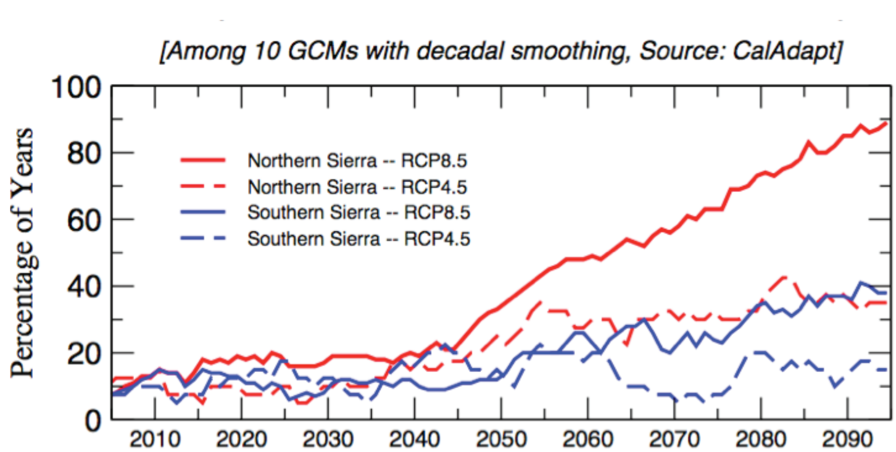
Changes in snow-water content projected for 2036-2065 (a, b) and 2070-2099 (c, d), under two greenhouse-gas concentration pathways into the future.

2.3 Snowpack Loss

As a result of projected warming, Sierra Nevada snowpacks will very likely be eradicated below about 6000 feet elevation and will be much reduced by more than 60% across nearly all of the range.

One of the defining features of the Sierra Nevada, the "Snowy Mountains", is its vast and long-lasting snowfields. Even though total precipitation is not projected to change substantially, the range's snowpack is universally projected to decline in response to warming, even in those climate projections that do include precipitation increases. Warming temperatures bring higher snow lines (the elevation above which rainfall gives way to snowfall during a storm) and more likelihood of rainfall rather than snow at any given location in the range, so that less of the range receives snow in the first place (Knowles et al. 2006; Feng and Hu 2007). In addition, there is more opportunity for early snowmelt, so that snowpacks do not accumulate or persist as long as under historical conditions. Together, these warming impacts yield ensemble-averaged patterns of declining snowpack amounts like those shown in Fig. 2.5 (Pierce et al. 2008). Any areas that appear in green, yellow, or red in these maps are projected to see snowpack declines, and the yellows into reds are areas where the average projection is that less than half of historical amounts of water will be present in future snowpacks. Snow is nearly eradicated below about 6,000 feet elevation (Fig. 2.4c). Only the highest peaks of the southern Sierra Nevada maintain amounts of snow that rival historical amounts by midcentury (Fig. 2.5b; Pierce and Cayan 2013), and by end of century snowpacks are reduced by 90% in most of the Sierra Nevada.

FIGURE 2.6



Projected odds that April snow-water equivalent (SWE) in the Sierra Nevada Range subregions will be fall within the historically lowest tenth, based on a 10-model ensemble of snowpack projections under two greenhouse-gas scenarios.

Notably, recent studies suggest that even those snowpack-loss projections are likely to be underestimates, due to positive feedbacks between warming trends and snow cover losses.

Walton et al. (2017) used a highly resolved climate- and surface-processes model of the Sierra Nevada to simulate snowpack responses to projected climate changes, in ways that allow the land-surface conditions to feed back upon air temperatures and weather. The result was even more loss of snowpack than projected by the "offline" hydrologic simulations used in Fig. 2.5 (and 2.6). The enhanced loss was due to the fact that when snowpack is reduced or melts earlier in the year, the color of the surface as seen from space is darker than it would have been had a typical historical snow cover been present. The darker surfaces reflect less solar energy than the snowfields would have, absorbing energy and warming more in the process. The surfaces in turn help to warm the overlying atmosphere more (and wind patterns may change), in ways that the hydrologic model used in Fig. 2.5 cannot represent, and the result is a feedback that warms the air more and consequently melts even more snow. Thus the projected snowpack losses shown in Fig. 2.5 are likely to be underestimates of the eventual real-world snow losses.

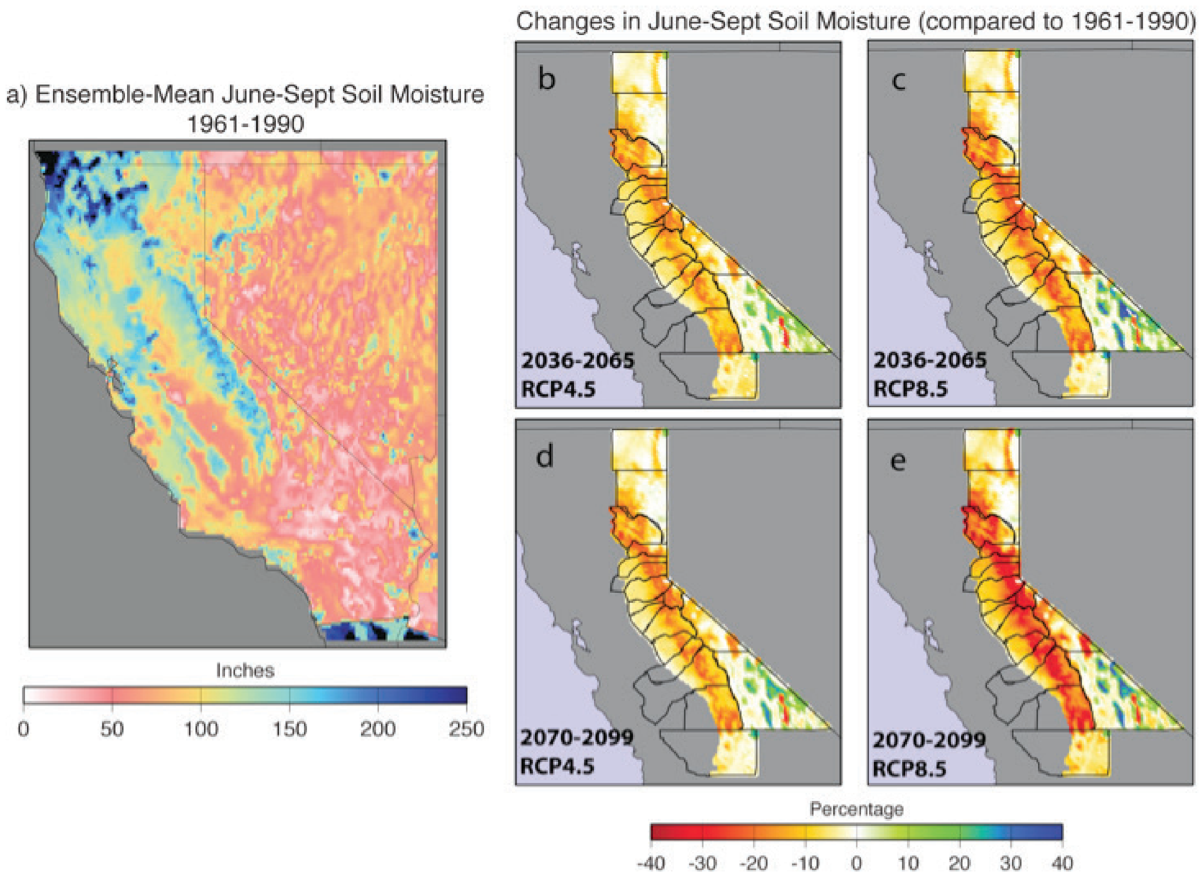
The measured Sierra Nevada snowpack was only 5% of its historical normal in April 2015, in part because of less-than-normal precipitation in that drought year but mostly because that was the warmest winter and spring ever measured in the region. The next lowest snowpack years historically were 2014 and 1977, when April snowpacks were only 25% of normal. With these extreme historical "snow droughts" in mind, Fig. 2.6 uses the 10-model ensembles of climate-change projections to estimate the changing odds of having snowpacks that would rank among the lowest 10% historically in the northern and southern Sierra Nevada. If greenhouse-gas concentrations continue to increase throughout the century (solid curves), such years will be almost continual in the lower, warmer northern Sierra Nevada and will happen four times as often as historically in the southern Sierra Nevada. If greenhouse-gas concentrations are reined in by mid-century (dashed curves), these low snowpack years will still occur four times more often than historically in the northern Sierra, but will remain mostly uncommon in the higher, cooler southern Sierra.

2.4 Regional Drying and Runoff Changes

These climate changes will combine to dry soils by from about 15% to as much as 40% below historical norms, depending on elevations, reducing soil and vegetation moisture, changing rivers and lakes, and ultimately challenging flora and fauna.

Between these changes in the snowpack and tendencies for greater evaporation of available moisture due to warmer temperatures, the hydrology (soil moisture, runoff, recharge) of the region is projected to change in ways that will impact geomorphology, flora and fauna, human communities, and water resources available to the region and the rest of the State. On the whole, the Sierra Nevada region will be much drier (Fig. 2.7; Cayan et al. 2010). As a result of warmer temperatures with corresponding tendencies for more rainfall and less snowfall, and earlier snowmelt, water will tend to exit the mountain catchments earlier in the year (Harpold et al. 2015). As a result of warmer temperatures and increased evaporation demands, the water that remains in the catchments is evaporated and used by plants more quickly so that by summer, soil and fuel moisture in the Sierra Nevada are projected to decline by 15% or more at the lower and highest elevations. Soil moisture is projected to increase by as much as 20-40% of their historical norms this century in a historically-moist mid-elevation zone (Fig. 2.4d) where historical snow cover is most substantially reduced or eliminated (Fig. 2.4c) by warming.

FIGURE 2.7

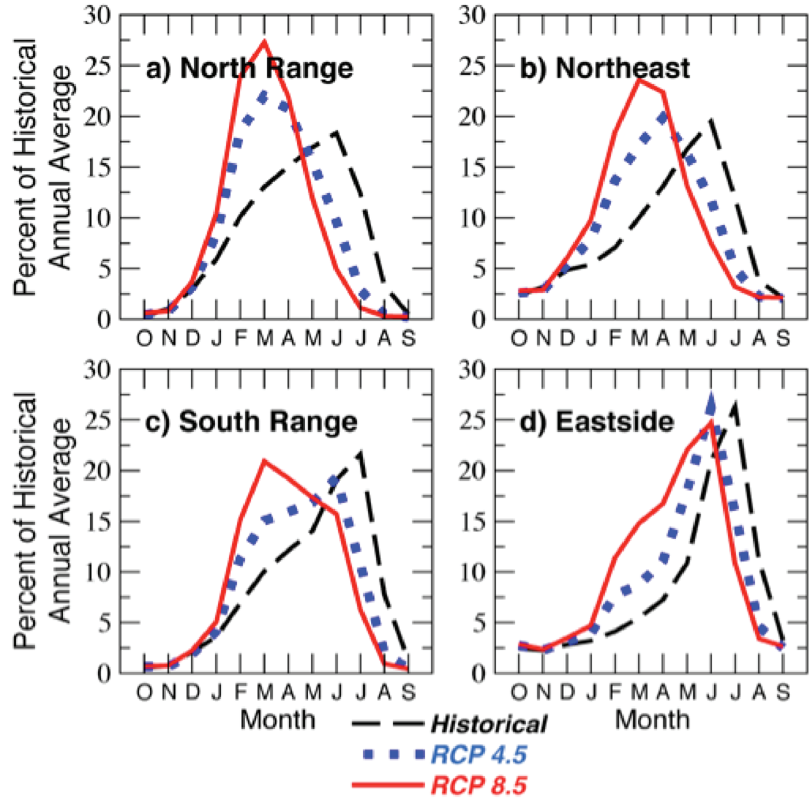


Ensemble averages of (a) historical simulations of June-September soil moisture and (b-e) projected soil-moisture changes simulated under climate projections from ten different climate models responding to two different greenhouse-gas futures.

Loss of snowpack and overall drying will lead to increased winter streamflows and floods, and to (largely compensating) reductions in warm-season flows.

Mean projected changes in runoff, by month of the year, are illustrated in Fig. 2.8, with changes in annual-total and seasonal-total runoff listed in Table 2.1. Annual-total runoff (available as surface water or groundwater) is projected to change modestly and, at this subregional scale, generally increases. These increases in runoff generation are a consequence of small precipitation increases (Fig. 2.1e-f) and the earlier snowmelt and rainfall, which allows more runoff to leave the range in winter and spring before the large summer evaporation demands that historically sap runoff rates (e.g., Dettinger et al. 2004). Fig. 2.8 illustrates this seasonal re-distribution of runoff from the Sierra Nevada that increases winter (and spring) runoff and decreases summer runoff rates. Winter runoff will be increased under all projections, because winter temperatures are warmer (Stewart et al. 2004; Fritze et al. 2011; Schwartz et al. 2017). This increase means more cool-season runoff from the range into reservoirs (when conditions are benign) or in the form of increased magnitudes and frequencies of floods (when not). By summer, the snowpack will be largely gone and water that has flowed out of the range in the cool-season is no longer available there, so that summer runoff, streamflows, soil moisture, and recharge are projected to decline dramatically with attendant overall-drying impacts on vegetation, communities, and the State's water resources.

FIGURE 2.8



Ensemble averages of 2070-2099 runoff hydrographs for the subregions shown in Fig. 1.1a—with each month's runoff shown as a percentage of the historical (1961-1990) annual-total norms--from ten climate models responding to two greenhouse-gas futures, where "runoff" is the water that avoids evaporation and use by plants to flow off or into land surfaces (essentially, surface water flows and groundwater recharge generated by a given area). Notably (d) Eastside responses shown mostly reflect snowmelt and runoff from the eastern slopes of the Sierra Nevada.

TABLE 2.1

	NORTHEAST	NORTH RANGE	SOUTH RANGE	EASTSIDE
	Water-Year Totals			
RCP 4.5	107 ± 18%	103 ± 17%	100 ± 20%	108 ± 22%
RCP 8.5	113 ± 27%	107 ± 26%	105 ± 36%	121 ± 47%
	January-March			
RCP 4.5	174 ± 38%	170 ± 41%	151 ± 39%	160 ± 36%
RCP 8.5	231 ± 86%	214 ± 81%	202 ± 100%	243 ± 137%
	July-September			
RCP 4.5	52 ± 9%	22 ± 9%	43 ± 18%	57 ± 19%
RCP 8.5	42 ± 6%	11 ± 6%	26 ± 16%	43 ± 21%

Average projected water-year and seasonal runoff (with ± 1 ensemble standard deviations shown), 2071-2099, by subregion in 10-model ensembles, as percentages of 1961-1990 simulated averages (corresponding to projected hydrographs in figure 2.8).

3: Major Vulnerabilities and Adaptations

A recommended strategy for developing adaptation options includes understanding historical trends, identifying vulnerabilities, developing strategies, and monitoring results.

Given the changes in climate described in section 2, adaptation will be necessary to sustain many natural and human communities of the Sierra Nevada. Climate change adaptation is "the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (McCarthy et al. 2001). Peterson et al. (2011) recommend the following steps for developing adaptation options to climate change in natural resource management:

- Understand current climate conditions and trends, as well as projected future climatic change, and how climate interacts with or influences resources and communities.
- Assess and rank the vulnerabilities of resources and communities to projected climatic changes.
- Develop and implement specific strategic and tactical adaptation actions.
- Monitor the effectiveness of actions (and inaction) and adjust management as needed.

Four categories of adaptation, in order of increasing intervention, are resistance, resilience, response, and realignment.

Millar et al. (2007) considered adaptation actions as targeting one or more of four different management objectives. Adaptation actions can:

1. Promote **resistance** to climate change: attempting to make ecosystems or resources impervious to climate change so as to maintain current or desired resource conditions;
2. Develop **resilience** to climate change: managing ecosystems such that they can "absorb" change and "snap back" to desired conditions after disturbance (Safford et al. 2012a);
3. Assist **response** to climate change: abet orderly transitions to new states by "working with" climate change and mitigating and minimizing undesired outcomes; and
4. **Realign** highly disturbed ecosystems: change ecosystems from their current state to a state more representative of a natural ecosystem or more likely to provide a set of key ecosystem services under anticipated climate change.

All of these adaptation categories have their place in policy and management, depending on circumstances and contexts. Overlap can occur between categories, particularly the 'response' and 'realign' categories; i.e., an action may fit into multiple categories. Thus, the goal is not to get caught up in classifying adaptations but rather to consider the full range of options for addressing vulnerabilities to climate change.

This report focuses on three major elements of the Sierra Nevada region: Terrestrial ecosystems and biodiversity, water resources, and human communities. The following sections quantify current climate related trends in these areas, summarize their key vulnerabilities to climate change, and describe adaptive measures that are being taken or contemplated in the region. Then we briefly discuss a few other issues and vulnerabilities.

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

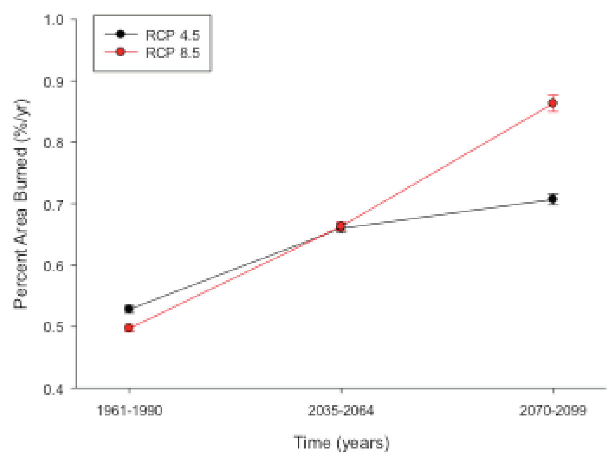
Even optimistic projections of warming lead to more wildfire, more drought stress, and lower carbon storage.

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.

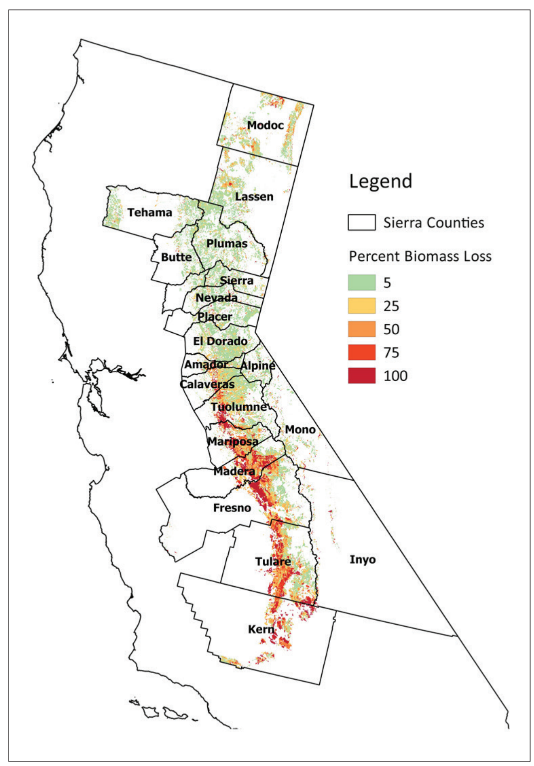
Weakened trees can facilitate bark beetle outbreaks (Preisler et al. 2017) with devastating results. As of 2017, drought-related mortality has killed almost 110 million trees in the Sierra Nevada region (Sierra Nevada Conservancy 2018). Mortality related to drought varied by county (Fig 3.1.2). The southern 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.

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

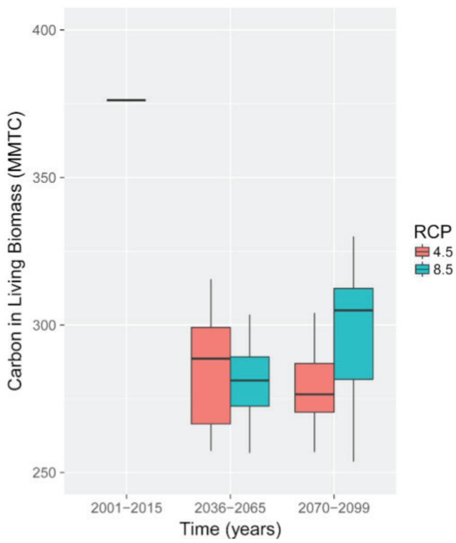
FIGURE 3.1.2



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).

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

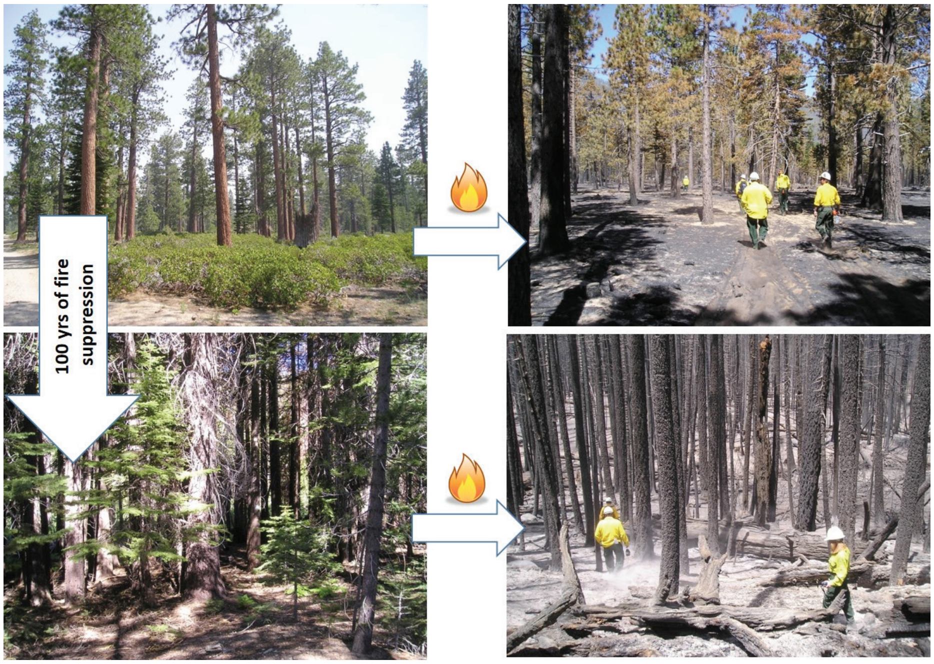
A wide-ranging portfolio of adaptation options is available to reduce the vulnerability of Sierra Nevada forests and woodlands to climate change.

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

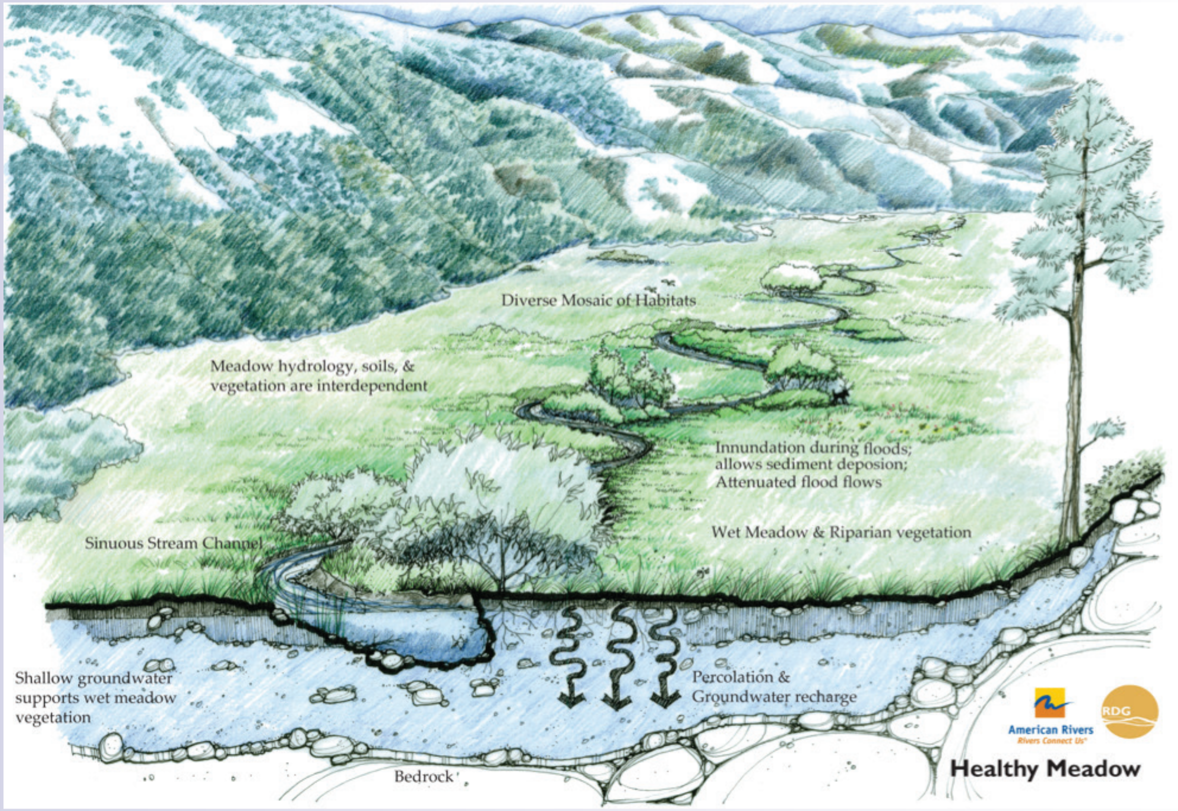
With increased flooding, reduced snowpacks and snowmelt, forest and habitat change (if not out-right loss), and longer drier summers projected to result from climate change, the benefits that accrue from meadow restorations will be of even greater value in the future. Added groundwater storage, improved 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.

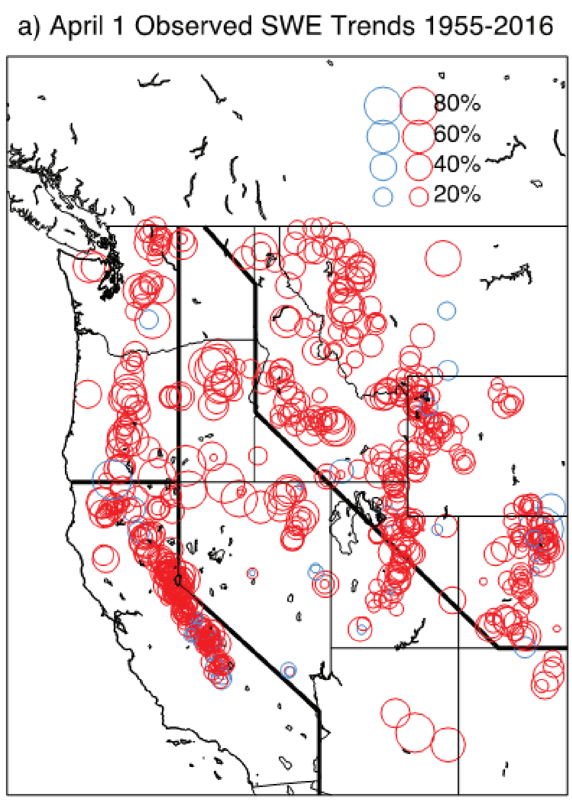
3.2.1.2 Snowpack

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

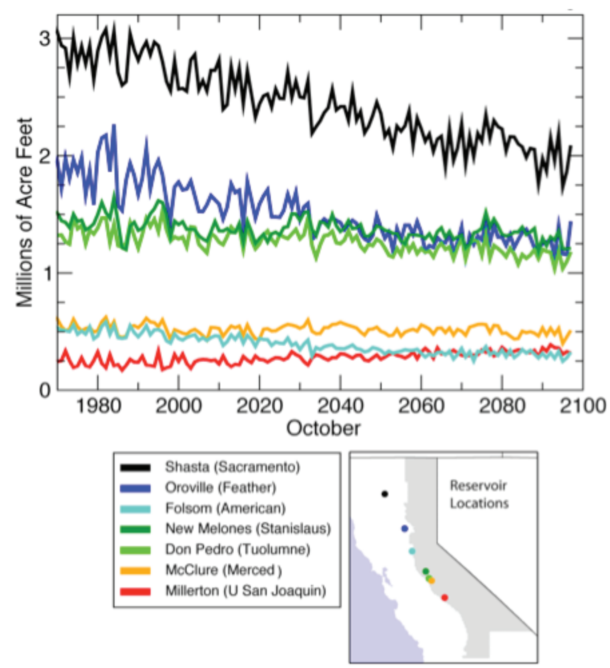
3.2.2.1 Surface-Water Supplies

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 assessed capacity and socioeconomic conditions in specific areas of the region. Efforts are underway as part of the IWRM Program to identify community capacity with specific attention to disadvantaged communities. Until the community-level assessment is complete, however, county level data are among the more comprehensive statistics available for understanding how climate change might affect humans in the Sierra Nevada communities.

Sierra Nevada-based water management groups (RWMGs) have used the Department of Water Resources median household income (MHI) threshold to identify approximately 122 communities considered "disadvantaged." This approach uses a limited income-based measure to delineate disadvantaged communities, and, as such, represents a starting point for understanding Sierra Nevada communities that are disadvantaged. Communities with 80% MHI ($49,191) qualify as disadvantaged. Communities with a combination of: 1) an 85% MHI threshold ($52,266); 2) a municipal population of less than 20,000, a rural county, or a reasonably isolated segment of a larger municipality with less than 20,000; and 3) financial hardship, an unemployment rate of 2% higher than the state average; or a low population density (100/square mile) are considered economically distressed areas. Several Sierra Nevada-based RWMGs recognize that nearly their entire region is disadvantaged (see Table 3.3.1).

TABLE 3.3.1: STATISTICS FOR COUNTIES IN THE SIERRA NEVADA

COUNTIES	2010 POPULATION	2016 POPULATION	BACHELOR'S DEGREE OR HIGHER, AGE 25+, 2012-2016	PERCENT UNDER AGE 65 WITH DISABILITY, 2012- 2016	CIVILIAN LABOR FORCE, % OF POP. AGE 16+, 2012-2016	MEDIAN HOUSEHOLD INCOME, 2012-2016	POP. PER SQUARE MILE, 2010
Alpine	1,175	1,071	29.7%	18.6%	48.4%	$62,375	1.6
Amador	38,091	37,383	21.5%	12.7%	45.5%	$57,032	64.1
Butte	220,000	226,864	26.1%	12.7%	55.4%	$44,366	134.4
Calaveras	45,578	45,171	20.2%	14.4%	48.4%	$53,502	44.7
El Dorado	181,058	185,625	33.0%	8.7%	59.3%	$72,586	106
Fresno	930,491	979,915	19.7%	8.8%	60.5%	$45,963	156.2
Inyo	18,546	18,144	24.5%	7.6%	59.1%	$47,278	1.8
Kern	839,627	884,788	15.7%	7.9%	58.5%	$49,788	103.3
Lassen	34,895	30,870	12.5%	13.8%	36.7%	$51,457	7.7
Madera	150,843	154,697	13.1%	8.5%	51.4%	$45,742	70.6
Mariposa	18,250	17,410	22.6%	11.7%	52.7%	$49,265	12.6
Modoc	9,686	8,795	18.3%	12.5%	50.6%	$41,194	2.5
Mono	14,202	13,981	30.6%	3.1%	72.1%	$58,937	4.7
Nevada	98,748	99,107	34.4%	9.7%	54.2%	$57,429	103.1
Placer	348,494	380,531	36.9%	6.6%	60.5%	$76,926	247.6
Plumas	20,007	18,627	21.9%	15.9%	51.7%	$50,125	7.8
Sierra	3,240	2,947	19.8%	15.5%	50.3%	$43,984	3.4
Tulare	442,182	460,437	14.0%	8.6%	58.4%	$42,789	91.7
Tuolumne	55,365	53,804	19.7%	14.7%	48.2%	$50,731	24.9
Yuba	72,148	75,275	15.5%	14.0%	54.6%	$48,739	114.2
California	37,254,522	39,536,653	32.0%	6.8%	63.0%	$63,783	239.1

Counties highlighted are considered disadvantaged or economically distressed areas. Rural county status is delineated by the Rural County Representatives of California (RCRC); (US Census Bureau 2016).

County level data are among the more comprehensive statistics available for understanding climate impacts on Sierra Nevada communities and show that 12 of the 20 counties in the Sierra Nevada qualify as disadvantaged or economically distressed. Calaveras County hovers at the threshold, though it is not considered distressed despite the community and landscape devastation caused by the 2015 Butte Fire. County data, however, masks considerable variation. A number of Sierra counties have both well off and impoverished communities. Madera, Fresno, Tulare, and Kern counties are home to significant populations, but Sierra Nevada statistics are skewed as their boundaries extend well into the San Joaquin Valley, with a majority of the population residing in the Central Valley.

3.3.1 TYPES OF RURAL, NATURAL RESOURCE-BASED COMMUNITIES

Be it a small town built around a lumber mill, an agricultural outpost, a Native American tribe (Box 6), or a collection of second homes surrounding a picturesque lake amidst forestland, the future of Sierra Nevada communities is inextricably linked to the natural systems that surround them.

BOX 6. TRIBES AND CLIMATE CHANGE

Native American Indian Tribes in and around the Sierra Nevada face many of the same issues regarding climate change impacts to natural and anthropogenic resources as other communities but often approach assessment and adaptation differently. Most federally-recognized Tribes have EPA-funded environmental departments and have varying capacity to manage and monitor important resources, such as water, open space, archeological sites, and air quality. Some tribes have already been aware of impacts of climate change on their important land and water resources for many years.

Given the complexity of the Sierra Nevada and their close ties to the land, each Tribe responds to environmental changes differently. Wildfire is a primary concern for tribes on both sides of the Sierra Nevada, and the Big Pine Paiute Tribe of Owens Valley, for example, recently upgraded its fire-response systems by increasing the size of pipes to fire hydrants and replacing most of its fire hydrants. Fires are common near and on the reservation, and this upgraded system will allow the tribe to better respond to blazes that threaten homes and other tribal resources. Some tribes are growing more food locally, both to decrease the greenhouse gases emitted during transportation and to build local resilience and self-reliance. The ongoing challenge will be ensuring that communication and collaboration occur between tribes and other natural resource agencies and stakeholders.

It is important to include tribes in decision making about issues and resources that may affect them and nearby communities. Tribes also maintain important knowledge about the history and status of ecosystems and experience with best management practices for adaptation. The inaugural indigenous-communities report of the 4th California Climate Change Assessment showcases tribes' innovative strategies and actions to address climate change, with a focus on traditional ecological knowledge (TEK; Goode et al. 2018).

3.3.1.1 Forest dependent

Many communities that are historically very forest dependent were hit particularly hard by the Great Recession of 2008-2009, but are banding together in community-based collaboratives to address shared problems, including climate change.

Sierra Nevada communities historically reliant on resource extraction and second-home development were hit particularly hard by the Great Recession of 2008-2009. Impacts carried well past the recession as rural community recovery lagged behind their urban counterparts. Mill closures in the central Sierra Nevada in the late 1980s and early 1990s put over 900 mill workers out of work. The decline in federal timber harvests and increased mechanization reduced mill infrastructure and human capital needed for forest restoration work. Capacity to complete forest work that would lead to more climate resilient forests was lost. Many young families have migrated from these areas, further depleting human capital and, with expected increases in fire frequency and severity, additional out-migration occurred with adverse economic and health conditions. As a result, many forest-dependent communities have reduced capacity to respond to the economic and ecological changes that climate change is bringing.

In response to economic and ecological challenges, however, community-based collaboratives are taking root across the Sierra Nevada to address the ecological, social, and economic landscape issues and climate change. For example, in Plumas and Lassen (and a small portion of Tehama) Counties, in 2017, stakeholders established a new collaborative to address fire- and watershed health across a 600,000-acre landscape. Other examples are the Amador-Calaveras Consensus Group (ACCG) and the Dinkey Collaborative (Box 7), started years earlier in the central and southern Sierra Nevada, respectively. The work of the ACCG helped spawn the non-profit California Healthy Impact Product Solutions (CHIPS) group to restore forests. CHIPS is now among one of the larger employers in Calaveras and Amador Counties and is a leading employer of Native Americans. Forest collaboratives, with a particular focus on restoring forest resilience, are playing a key role in rebuilding capacity of communities to respond to climate change impacts. Other challenges these groups must overcome include entrenched agency cultures that have been resistant to change and frailties associated with low levels of existing community capacity.

BOX 7. LOCAL PERSPECTIVE: DINKEY LANDSCAPE

The Dinkey Landscape Restoration Project, the first Collaborative Forest Landscape Restoration Project in California (there are three total), covers approximately 150,000 acres in the southern Sierra Nevada in eastern Fresno County. This is a diverse ecological area with oak woodlands, foothill chaparral, mixed conifer forests, and mountain meadows. A number of local communities, including North Fork, Prather, Shaver Lake, and others, are directly tied to this landscape.

Climate-linked events are already affecting these communities with mixed results. As an early example, the Dinkey landscape has been hit with massive tree mortality over the past few years. While the cleanup effort has resulted in a short-term surge in employment, work exceeded local capacity and loggers from all over the country are now working in the area. The service and hospitality industries are flourishing, while timber landowners and the tourism industry face losses. The capacity of these communities will be an important factor in how climate change affects them. Community capacity, including financial, human, social, cultural, and physical capital, will determine how these communities are able to respond to this and future impacts.

Across the Dinkey landscape, there are very few young families moving to the area and many residences are "second homes," seasonal residents who are less likely to invest in the community. Enrollment in free and reduced-price meal program at local schools is high, with some local high schools seeing 100% enrollment in recent years. Data points like these highlight the capacity challenges that impoverished rural communities face as they are forced to respond to climate change impacts.

3.3.1.2 Agriculture dependent

Some of the region's communities are economically and culturally tied to agriculture and thus are especially dependent on stable water supplies and reliable weather.

With fertile areas extending to the foothills of the Sierra Nevada and large montane valleys, some Sierra Nevada communities are closely tied to the land through agriculture, both economically and culturally. With approximately 30% of its labor force employed in agriculture (US Census Bureau 2016) and 53% of the county's land use (USDA 2012; Madera IRWMP 2014) involved in agriculture, Madera County is an example of an agriculture-dominated county.

Agriculturally dependent communities rely on a stable supply of water and predictable weather, but climate change offers an uncertain future likely involving more drought and floods. In addition to foothill communities, mountain valleys throughout the Sierra Nevada are reliant on agricultural economies. For example, nearly 200,000 acres are used for hay and livestock production in Sierra Valley, the highest large valley in the Sierra Nevada. Prospects for increased flooding on the valley floor, as well as agricultural water users' historic (and potentially growing) reliance on groundwater for domestic and agricultural water demands, make climate change a major water-management challenge. Reducing groundwater overdraft and planning for flood protection are top priorities (Madera IRWMP 2014). In addition to existing water and infrastructural capacity limitations, the full range of impacts from climate change is likely to stress the financial capacity of these communities as reliable returns on investments in agriculture become less reliable. Many agricultural communities, similar to their forest-dependent counterparts, also face capacity challenges associated with aging populations.

3.3.1.3 Tourism dependent

The economies of tourism-dependent communities depend on snowpack, stream and lake conditions, and forest health; wildfires can be particularly devastating.

Communities dependent on tourism and dominated by second-homes and resorts, such as the Lake Tahoe Basin, will also to be affected by climate change in similar and different ways. Bimodal socioeconomic conditions (wealth disparities) characterize many of these communities, with segments of the population well off and others, typically service workers, poor. As an example of this, in 2010, Tahoe Regional Planning Authority reported housing-affordability challenges greater than in the San Francisco Bay Area, that reached nearly 80% of households in parts of the Lake Tahoe Basin, as a result of low-wage, part-time jobs and high housing prices driven by second-home ownership (Applied Development Economics Inc 2015; TRPA 2013). Loss of skier-days from drought and diminished snowpack will likely affect the availability of service jobs. Fire and insect outbreaks can affect property values as well as tourism expenditures.

Wildfires can be devastating to tourism-dependent communities. In August 2013, the Rim Fire affected communities in Mariposa, Tuolumne, and Calaveras Counties, destroying private and commercial structures, devaluing real estate, and causing extensive revenue losses for businesses inside and adjacent to Yosemite National Park for the final three weeks of summer. Park tourism continued to be affected through October. Similarly, the Chips Fire of 2012 choked the Lake Almanor basin with thick smoke for weeks, shutting down tourism and businesses for the economically critical month of August.

Adaptation solutions for winter tourism-dependent communities could include transitioning away from recreational economies reliant on snow and developing more snow-free season recreation opportunities. Recent summer-tourism investments by ski areas in the Tahoe Basin and the eastern Sierra Nevada suggest they are already pursuing this strategy. Some ski areas have begun tailoring their slopes to smooth them so that skiing is still possible with recent smaller-than-historical snowpacks to buttress their winter-recreation opportunities. Mammoth Mountain Ski Area has expanded its summer mountain bike park operations to take advantage of more of the snow-free ski area. At Lake Tahoe, efforts are afoot to improve shoreline environments to improve access in the face of greater lake-level swings and to preserve near-shore water clarity and quality. Benefits from more climate resilient forests, such as improved and wider viewsheds, may provide other opportunities to accommodate climate-change impacts, though these benefits may be particularly difficult to predict or encourage.

3.3.2 COMMUNITIES AND WATER-RELATED VULNERABILITY

Water uses and sources differ from community to community and will be affected by climate change that threatens surface-water and groundwater supplies, quality and infrastructure.

Changes in the amount, timing, and type of precipitation (e.g., rain vs. snow) will impact annual runoff and storage capacity in many watersheds and for many communities and will lead to increased rates of groundwater withdrawal, with potentially adverse effects for rural residents. In the Upper Feather River watershed, for example, many residents rely entirely on private wells, and are susceptible to water-related impacts of climate change (Box 8). Mariposa County, in the southern Sierra Nevada, exemplifies the challenges faced by Sierra Nevada communities in drought-prone environments under a changing climate. With attractions like Yosemite National Park, the area is a renowned tourist destination with an annual influx of over 3.8 million visitors, and with most visiting during prime tourist months. In addition to the service industry associated with tourism (e.g., hotels, restaurants, and guest services), agriculture, forestry, and fishing are contributors to the economy. These industries all depend on reliable surface and groundwater supplies. Decreased water supplies stemming from increased water usage, coupled with increased drought associated with climate change, could severely impact the county's environment and economy of gateway communities. Unfortunately, limited data are available to quantify current supplies and provide projections for comprehensive planning and mitigation efforts. Other general water-related impacts from climate change directly affecting rural communities include water quality, infrastructure integrity, and severe financial burdens.

BOX 8. LOCAL PERSPECTIVE: UPPER FEATHER RIVER WATERSHED

The Upper Feather River watershed (UFR) is a 2.3 million-acre basin in the northern Sierra Nevada and southern Cascades draining to Lake Oroville, the California State Water Project's largest reservoir. The UFR encompasses Plumas County and portions of Butte, Lassen, and Sierra Counties. The Upper Feather is the supply for virtually all the water delivered by the California State Water Project, supplying water to twenty million people and agricultural users. Two incorporated cities (Portola and Loyalton) are contained within the UFR, in addition to roughly 37 unincorporated communities. Twenty of the 68 Census Bureau designated places qualify as disadvantaged, with annual median household incomes (MHI) less than 80% of the statewide average. Using an annual MHI less than 60% of the statewide average, half of those communities qualify as severely disadvantaged.

In a changing climate, threats faced by these communities are multiple and interactive. The Forest Service reported that the 100-square mile Moonlight Fire, which burned in late summer of 2007, converted 44 percent of the burned area from old forest to chaparral. Rising temperatures, prolonged drought, and higher fuel loading may result in up to a doubling of the burned area within the UFR by the year 2050. Firefighting personnel are limited in many communities, shifting the burden of incident response onto the communities themselves, most served by volunteer firefighters and limited water supplies. Flooding and erosion typically follow fire incidents, endangering human life, property, and water quality.

Changes in the amount, timing, and kind of precipitation (e.g., rain vs. snow) are already affecting annual runoff regimes and storage capacity within the UFR. Pacific Gas & Electric has reported cumulative diminished surface and subsurface flows over the last 60 years. Stressed surface water resources will likely lead to higher rates of groundwater withdrawal, with potentially adverse impacts to rural residents, many of whom rely entirely on private wells. Past drought events in the UFR have resulted in dry wells, especially in low-income areas, requiring well drilling and water deliveries. Within the UFR, the Lake Almanor Watershed Group and the South Lassen Watersheds Group have formed to address issues related to water quality, quantity, and forest health, including catastrophic wildfire risk mitigation.

Capacity to address current and future water challenges also differs from community to community, and is limited in many of the more disadvantaged rural communities.

Aging infrastructure, leaks, poor pressure, and bacteria are challenges that many rural water purveyors already face. Without the technical capacity and capital for planning and implementing needed improvements, systems are falling into disrepair and failing. Sewer services in some areas are plagued with aging infrastructure, deferred maintenance, and increasing regulatory requirements and costs. The inability to connect the hundreds of small systems makes sharing resources challenging. Individual wells and septic systems in disrepair increase the likelihood of drinking water contaminated with nitrates, arsenic, perchlorate and other toxins. A number of communities have a history of unsafe drinking water and are subject to frequent "boil water" advisories. Additionally, systems in disrepair and lack of capacity to address problems can lead to contamination and algal blooms in destination lakes, threatening recreation experiences and economies.

Rural communities with reduced capacity are further challenged to adequately respond to water-related impacts from a changing climate. Many communities lack financial capital to repair and maintain functional water systems and replace failing wells (Ekstrom et al. 2018). The high cost of water, reliance on bottled water, and ever-rising cost of water treatment will only exacerbate these conditions. Communities are also challenged by isolation from dialogue and representation, leading to a lack of awareness of water issues facing some communities, barriers to resource procurement, and lack of acknowledgement of tribal water rights.

3.3.3 COMMUNITIES AND FOREST/WILDFIRE VULNERABILITY

3.3.3.1 Wildfire risk

Combined effects of drought, decline in forest health, and wildfire—all of which climate change will exacerbate--threaten life and property of communities, especially in the wildland-urban interface throughout the region.

As described in section 3.1, years of drought, declining snowpack, and increasing temperatures, combined with more than a century of fire suppression and attendant changes in forest composition, have significantly increased fire severity, frequency, and size throughout the region. Government agencies that manage much of the land face regulatory, financial, and personnel restrictions limiting their ability to actively manage the millions of acres of land for which they are responsible. Though out-migration is a significant issue in certain parts of the Sierra Nevada, in-migration and development pressure characterize other areas, especially in the central and southern parts of the range. Communities typically have limited capacity for incident response, especially in the early stages of a fire outbreak, straining local resources and budgets.

Mandatory evacuations in the Sierra Nevada region have and will continue to become more common, and homeowners will face increasing difficulties insuring their homes in these high-risk areas, or pay increasingly high premiums (Dixon et al. 2018), limiting regional affordability for older and less affluent demographics. All communities but especially tourism-dependent communities suffer when active fire, smoke, and ash close facilities during the high season, constraining a critical economic sector. In the aftermath of fire, especially large-scale high-severity fires, communities may be threatened by mudslides, flooding, and the impacts of erosion on water quality and infrastructure integrity. As with wildfire, these situations test the capacity of limited local emergency response resources, and in too many cases can overwhelm communities lacking resources to prepare and respond.

3.3.3.2 Forest Restoration

Inadequate capacity to restore forest health (including more natural wildfire intensities and extents) limits land-management options for preparing for climate change. Inadequate capacity (e.g., at remaining mills) to economically remove and use byproducts (wood and other biomaterials) of forest restoration is a primary challenge to restoration throughout the region.

One of the primary challenges to reducing fire threat is inadequate capacity to utilize material that needs to be removed from the forest. As fire suppression and selective logging historically altered the structure of forests, and as environmental restrictions reduced access and management, prolonged drought, a changing climate, and beetle infestations have increased tree mortality and risk of catastrophic wildfire. The economic impacts of the declining timber industry in the 1980s and 1990s were softened by an increase in tourism and construction of second homes. This lasted until shortly before the Great Recession.

Mill infrastructure and forest industry workers decline as one travels north to south in the Sierra Nevada. In the southern Sierra, where forest mortality is highest, mills and timber industry workers are few. This is the reason out-of-area and even-out-of-state contractors have traveled hundreds of miles to harvest dead trees in the area. An opportunity for putting local residents back to work is being lost.

Governor Brown recognized in his 2015 Proclamation of a State of Emergency that there is a desperate need to thin forests to reduce the risk of catastrophic wildfire and maintain the health of vital watersheds. With over 129 million trees dead (U.S. Department of Agriculture, Forest Service 2017) and following more devastating fires in May 2018, Governor Brown issued another Executive Order (B-52-18) to "Protect Communities from Wildfire, Climate Impacts." This order called for, among other things, doubling the land actively managed, and expanded grants, training and other means to improve watersheds, and supporting innovative use of forest products by the building industry.

Remaining mills in the Sierra Nevada and Central Valley lack the capacity to handle much of this wood because they are inundated with recent wildfire salvage, as well as material thinned to protect their own industrial timberlands. Most bioenergy facilities are distant from the forest and it is expensive to move chips to these power plants. Reducing wildfire risk and restoring forests is expensive and labor-intensive, as small-diameter trees have little commercial value. Agencies also have lost of much of their capacity to remove this material. Reintroduction of fire on the landscape is needed, but in many areas fire cannot be safely introduced without first reducing density.

With few outlets for small woody material, the disposal of forest restoration byproducts is often accomplished through open pile burning that generates harmful emissions and short-lived climate pollutants, such as black carbon. Wildfire and especially the catastrophic fires of recent years also impact air quality, producing fine particulate matter, carbon monoxide, and volatile organic compounds, among other air pollutants. The town of Portola, located in eastern Plumas County, was recently designated as a "non-attainment" area by the Northern Sierra Air Quality Management District. Low capacity communities are affected when pollutants from wildfire and pile burning are combined with wood stove and other emissions and result in out-of-compliance days and ultimately fines and the suspension of transportation infrastructure upgrades.

As climate changes and forests are increasingly threatened by high-frequency, high-severity wildfire, communities can benefit from building and maintaining infrastructure that facilitates a suite of forest management activities, including green timber sales, restoration, and salvage logging. Increased "woods work" will not only improve forest health and community safety, but maintain an important source of regional income. Local economies stand to benefit through local contractor and workforce development, and also from revenue sharing with the USFS, which has historically contributed 25% of its timber receipts to rural counties as a means of compensation for their large, non-taxable land base. In 2014, California's National Forests generated nearly $2 billion in local labor income. An estimated 20% of these funds were generated through the sale of forest products and county payments (https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd551249.pdf). Ensuring that much-needed restoration and adaptation work is accomplished in the face of climate change, with potential benefits both for ecosystems and communities, requires the use of new and old tools and authorities, collaborative processes, efforts to expedite environmental analysis that can take more than five years to complete, and increased political will.

3.3.4 HEALTH VULNERABILITIES

Climate change may impact quality of health and well-being, including physical and mental health, of the region's populations.

At the extreme, issues that may impact the quality of life and well-being of people in the Sierra Nevada region as a result of climate change, may include food insecurity, food contamination, decreased access to clean water, reduced access to shelter and basic services, and displacement and/or migration (Lewis and Ballard, 2011). Populations with physical disabilities have increased vulnerability to these impacts, especially elderly and children with disabilities and their caregivers (Smith and Notaro, 2009).

Fire-related emissions, whether they originate from pile burning or wildfire, affect the health of sensitive populations in Sierra Nevada communities. Exposure to fire emissions can exacerbate asthmatic conditions, cause respiratory and cardiovascular illness, and increase rates of premature death (Wettstein et al. 2018). Combined with high poverty rates and limited access to comprehensive health care services, the effects of wildfire are especially taxing in areas with poor health and low adaptive capacity.

Other than fire emissions, direct and indirect climate change impacts on human health may be many and varied. Catastrophic wildfire and flood events will increase sedimentation of reservoirs. Sedimentation from historic mines have toxic heavy metals that disproportionately affect those tribal and ethnically diverse populations in the Sierra and the foothills eating contaminated fish (Sierra Fund 2008). With changed precipitation regimes and increased flood events, downstream water users are also threatened by aged and now unmanaged debris dams that hold back this sediment (Martin and Monohan 2018). Rates of depression, anxiety disorders, post-traumatic stress disorders, substance abuse, and suicides may rise as the effects of climate change worsen. Field and others (2014) suggest that the mere knowledge of climate change may lead to anxiety and despair in some people.

Age, disability, and geographic/social isolation may aggravate climate-change challenges and limit responses among the region's population.

More than 10% of the population of the less-populous counties (<200,000 people in 2016) in the Sierra Nevada region is over 65 years old (Table 3.3.1), a total that is over 50% higher than in the state as a whole (Table 3.3.1). Since aging impairs muscle strength, coordination, cognitive ability, the immune system, and the regulation of body temperature, and often finds populations socially isolated or dependent on caretakers, people aged 65 and older are especially vulnerable to the health impacts of climate change (Nitschke et al. 2013). Elderly populations, especially those with limited income or mobility, have increased risk of heatwave- and flood-related health impacts. With general trends towards drier conditions (section 2.4) and historical diversions of streams away from lakes and playas, dust storms present air quality and thus health concerns (Crooks et al. 2016).

Health impacts from heat waves and poor air quality are likely to be enhanced by climate change.

The Sierra Nevada region is also home to many people and communities, generally distant from medical services and often in difficult-to-evacuate settings. Most people living in the range itself are in areas with high-risks of wildfire; for example, 55% of the population in Sierra County (Northern Sierra Nevada subregion) and 83% in Mariposa County (Southern Sierra Nevada subregion) live in wildfire-hazard zones (from assorted reports by Maizlish et al. 2017).

These counties are not unique. Populations in the southern Sierra Nevada are exposed to some of the worst ozone levels, and are just downwind from the worst particulate-matter loads, in the state (CalOES 2018). Climate change may aggravate the potential for extreme air-quality events in the future.

Finally, sustained heat waves are expected to increase in frequency, intensity and duration under climate change scenarios, with the number of major heat waves more than doubling (Sheridan et al. 2012). Heat waves directly affect human health through heat-related illnesses, such as heat stroke, heat exhaustion, and dehydration, as well as other illnesses and premature deaths from cardiovascular or respiratory diseases. Heat waves are associated with increased hospital admissions for cardiovascular, kidney (including kidney stones), mental health, diabetes, and respiratory disorders (Basu 2009). The health impacts of these changes will be complex and highly variable; however, a new tool, the California Heat Assessment Tool, has been developed to provide alerts for potential deleterious heat-wave impacts at very fine resolution (Steinberg et al. 2018), considering regional differences and differences among various segments of populations. Although warmer temperatures are likely to impact a wide range of populations (Kovats and Hajat 2008), the most vulnerable subgroups include: the elderly, children, those who work outdoors, those with lower socioeconomic status, those who are socially or geographically isolated, and those who lack resources or opportunities to prepare and adapt to these challenges (e.g., by use of air conditioning).

3.3.5 ADAPTATION ACTIONS

Among the most encouraging signs regarding adaptation to a changing climate are the rise of collaborative groups and, more recently, a new openness to these groups by land management agencies.

Initial shifts toward more adaptive institutional frameworks are increasingly evident across the Sierra Nevada, acknowledging and learning that collaborative approaches will be integral to climate adaptation. Climate changes will burden not only ecosystems and communities but also the institutional contexts in which they operate. Institutions, like forests, will need to adapt to be more resilient to disturbances. A transition to institutions that are increasingly responsive to community concerns is needed, with conscious attention to impacts on social cohesion and community character. By leveraging collaborative capacity, future institutions will become more capable of providing nimble, locally driven, and sustainable responses to changing climate conditions.

3.3.5.1 Forest management institutions

New policy and programmatic innovations are providing tools and authorities to accelerate forest-management efforts, including stewardship authorities and community-responsive contracts.

Forest management, particularly on public lands, has been slow to adapt to changing ecological conditions and societal expectations. However, in recent years a number of policy and programmatic innovations have provided new tools and authorities enabling managers to accelerate the amount of work in the woods. Stewardship Authority, for example, has allowed the USFS to blend needed restoration work with commercially viable timber extraction—objectives traditionally achieved through separate contracts. As stated in the program's original ten-year authorization (and extended to 20 years in recent legislation), these blended contracts aim to "achieve land management goals for the national forests and the public lands that meet local and rural community needs." Rural community needs can be addressed in part through local contractor hires and the resulting increases in employment and economic activity.

Long-term stewardship contracts are also a pre-condition for investment in the infrastructure needed to restore over-stocked forests with little commercially valuable timber. Small-diameter wood is often removed in the course of stewardship projects, but ultimately its low market value decreases profit margins for contractors and reduces the revenue available to carry out other non-timber management objectives. Small-scale bioenergy facilities, and co-located businesses (e.g., firewood, post and pole, etc.), are therefore logical complements to stewardship contracts, providing local employment by making use of low-value end- and by-products. Pairing biomass energy production with community-scale manufacturing can increase the volume of hazardous fuels material (such as small diameter wood and slash) removed from densely stocked stands, and create more jobs for local residents. Such an approach simultaneously reduces a community's likely exposure to impacts of climate change and high-severity wildfire and rebuilds community capacity, creating a positive feedback loop that helps empower communities to address future climate impacts.

The combination of community-responsive contracts and investments in community- scale wood utilization demonstrate commitments by policy makers and agency officials to increasing the pace and scale of restoration. However, agencies are only beginning to leverage community capacity in forest restoration and to devise meaningful ways of measuring associated benefits. These are components necessary for achieving sustainability and climate resilience and tying much-needed woods work to real financial and social benefits for the communities that depend on the resource.

3.3.5.2 Collaborative forestry

Stakeholder collaborations and community-based organizations are developing in the region to improve capacity and options for landscape-scale cross-boundary forest management and restoration.

From the northern edges of the Sierra Nevada in the Lassen National Forest to the south in the Sierra National Forest, diverse groups of stakeholders have begun collaborating to navigate social, political, and environmental changes. Successful collaboration at the community level promotes restoration that improves the resilience of forests and capacity of communities to effectively respond to climate change. More than ten collaboratives are working to address key barriers to forest restoration through development of systematic solutions, effective utilization of existing tools and innovative approaches to achieve the type of landscape-scale, cross-boundary restoration that is necessary to maintain healthy resilient forests, and, if necessary, management for orderly responses and realignments in the face of climate change.

Community-based organizations are providing additional capacity, working to achieve "social license" to enable projects to move forward, and exploring ways to increase agency capacity to implement forest restoration projects. In the northern Sierra Nevada, collaborative groups are engaged in environmental planning for forest restoration–helping the U.S. Forest Service to do work it otherwise would not have the staff to carry out (e.g., Box 9). In the central Sierra Nevada, state and federal agencies are partnering as part of the Tahoe-Central Sierra Initiative to conduct fuel treatments along the Highway 50 corridor, restoring ecosystem resilience and protecting communities. Farther south, Tuolumne County and the Stanislaus National Forest have established a Master Stewardship Agreement to pursue collaboratively identified projects that promote forest resilience within the Stanislaus National Forest.

BOX 9. FIRE MOU PARTNERSHIP

This unique, voluntary collaboration grew out of the settlement in 2015 of a longstanding lawsuit between environmental organizations and the Forest Service. Beginning with 11 members but growing to over 25 since 2015, and led by Sierra Forest Legacy, this Partnership of members with a wide diversity of interests ranging from air quality to private lands and natural resource perspectives now works towards increased use of fire to meet ecological and other objectives in Sierra Nevada forests. The Partnership promotes efforts to increase the information base for decisions about controlled-fire use, lowering of barriers to its use, and collaborative actions across jurisdictions and agencies. In addition to the increases in acreage treated with controlled burns in 2017, the Partnership also reports increases in cross-jurisdiction collaborative burning with the Forest Service, CAL FIRE and private contractors. These efforts are often focused in the wildland-urban interface, and use preemptive fire to protect communities and restore a more natural fire regime. A good example is in the Dinkey Creek Collaborative landscape where, based on a request from a broad group of stakeholders, the Forest Service committed to support 10,000 acres of prescribed fire in 2017/2018. In addition to increasing acreages burned, the Partnership is working to recognize the air-quality benefits accrued with controlled burning compared to unplanned fires of uncontrolled and uncharacteristic scales and intensities. In fact, three recent additions to the Partnership are the El Dorado, Placer, and Butte County Air Quality Management Districts.

Communities are speaking up to agencies for triple-bottom line prioritization that balances social, economic, and ecological goals.

Many rural communities are making their voices heard in ways they haven't before, leading to policy innovation (such as the establishment of the Collaborative Forest Landscape Restoration) that balances "triple-bottom line" (social, economic, and ecological) outcomes. These efforts have led to policy innovation, fostered collaboration between groups with diverse views, and accelerated technology research and development. However, shifts in agency culture and society at-large take time. As state and federal resources are further stretched to respond to climate change impacts, continued evolution of the collaborative approach, with an eye toward co-management, will be necessary to maintain and restore communities and ecosystems.

3.3.5.3 Interlinked challenges and integrated responses

Ecosystem health, economic health, community health, and human health are interlinked in the context of climate change. Thus, integrated strategies (like IRWM programs) and rebuilding of community capacities are critical to climate change adaptation in the region.

While the biophysical effects of climate change to Sierra Nevada ecosystems are more commonly studied and reported, the important links between ecosystem health, community health, human health, development and land-use strategies, and climate change in rural communities are a growing concern throughout the Sierra Nevada region (e.g., Box 10, Box 11). Adverse impacts on natural resources will increase the vulnerability of rural economies that themselves are built upon availability of resources. Furthermore, general health and wellbeing is at risk as residents of rural communities directly experience the effects of intense drought or increased flooding events (such as well-water shortages, failing water infrastructure, and costs in addressing these issues) or catastrophic wildfire—whether it's homes that are burned or residents who face health-compromising emissions. Limited capacity further challenges communities struggling to adapt to all of these effects.

BOX 10. CLIMATE-SMART LAND TRUSTS

Land management decisions and commitments play—intentionally or not—important roles in reduction (mitigation) of the coming climate changes and in preparing landscapes and communities for those changes. Well informed and planned decisions and land stewardship can increase the capacity of Sierra Nevada landscapes and communities to adapt to climate change, as well as contributing to sequestration of carbon and reduction of energy footprints. A number of communities and institutions (e.g., Point Blue Conservation Science and the California Council of Land Trusts; www.calandtrusts.org) are working in partnership with federal entities and land trusts to

- encourage and facilitate the incorporation of future-climate information and challenges into conservation planning (informing acquisition priorities and developing a community of climate-smart stewards and partnerships);
- develop climate-smart conservation easements (targeting conservation efforts on locations and methods that will be most resilient to climate change);
- provide landowners with information, legal tools, links to grant opportunities, and technical assistance that help promote land stewardship that addresses multiple stressors and challenges including but not limited to climate change;
- promote monitoring and evaluation of the results of land-stewardship efforts (because we're all still just learning how to do this); and
- encourage public agencies to spearhead regional partnerships and efforts to improve outcomes, reduce inefficiencies and duplications, and entrain new funding sources.

BOX 11. CLIMATE-SMART LAND DEVELOPMENT

As more people move into the Sierra Nevada in years to come, climate change is going to be an increasingly important consideration, and wise planning and developments can go a long way towards reducing greenhouse-gas emissions and accommodating and adapting to the climate and landscape changes to. Climate change is already challenging the safety and sustainability of Sierra Nevada communities, and its impacts will be even more severe if communities and developments aren't designed from the start in ways that minimize hazards through thoughtful land-use planning and parcel-level design.

In terms of climate-smart land development and planning, the Sierra Nevada Alliance (www.sierranevadaalliance.com) has recommended these actions in their Sierra Climate Change Toolkit (2010):

- Promote infill and transit-oriented development, to reduce transportation emissions and expansion of disruptive and vulnerable "urban-wildland interface" areas.
- Encourage contiguous outward growth, to reduce expansion of urban-wildland interfaces.
- Don't build in unsafe places, avoiding steep and unstable surfaces and wildfire traps.
- In unsafe places, at least build in safe patterns avoiding undue isolation from important services, and avoiding growth in flood zones, and wildfire traps.
- Adopt climate-friendly building codes.
- Build water-wise communities to increase flexibility and margins-for-error in the face of continuing climate-change uncertainties.
- Integrate land-use planning into water planning, and vice versa.
- Bring public-health officials, disadvantaged communities, fire agencies, and emergency agencies to the planning table.
- Support open space, working landscapes, and important habitat.
- Ensure that building structures withstand future hot and cold extremes.
- Ensure surface water will flow on and off properties in ways, and along paths, that reduce flooding and protect downstream watershed areas.

For far more detail about climate-smart development, consider the Sierra Nevada Alliance's Planning for Water-Wise Development in the Sierra: A Water and Land Use Policy Guide, Dangerous Development: Wild re and Rural Sprawl in the Sierra Nevada, and Planning for the Future: A Sierra Nevada Land Use Index reports. The Sierra Green Building Association (SiGBA; http://www.sigba.org) is an organization that promotes well-designed environmental buildings and business practices for sustainable lifestyles in the Sierra Nevada region.

Governor Brown recognized in his 2015 Proclamation the need to conduct wildfire cost-avoidance and cost-benefit studies, and modified grant criteria for the IRWM program to encourage spending on watershed health projects. Never before has there been an investment commitment by the State of California (through the California Climate Investment fund) that targets, among other projects, forest and environmental restoration and economic development. The challenge now is not only identifying needed projects, but rebuilding rural manufacturing capacity and re-aligning agencies, collaboratives and investments, and targeting investments in ways that will make a real difference in the forests and watersheds that need it most.

3.4 Some Additional Vulnerabilities

Increased heat and precipitation extremes are expected to impact the region's transportation and other infrastructures.

The Sierra Nevada region's transportation and energy infrastructures were developed to accommodate its highly variable climatic conditions, but are frequently challenged by natural events, including earthquakes, storms, and floods. Climate changes may result in increased maintenance and repair expenditures, disruptions of economic activity, interruptions of critical lifelines, and ultimately reductions in the overall quality of life for Californians (CNRA 2008). Impacts on transportation infrastructure from warming include softening or buckling of road pavement and deterioration of concrete structures, compromising roadway integrity during heat waves or reducing their useful lifetimes (CDOT 2013). Similarly, bridge joints and other structural elements expand and contract during periods of extreme heat and cold, requiring maintenance and reducing their useful lifetimes. Heat waves and overall higher temperatures are likely to challenge vehicles of all sorts, from automobiles to railways, increasing the frequency of breakdowns and reducing service lifetimes. More frequent or intense heat waves also may contribute to increased incidents of vehicle-emitted smog and poor air quality. Heat waves can lead to limitations or interruptions to construction activities.

However, some areas will experience benefits from increased temperatures, like reductions in snow and frost seasons that may reduce the need for removing snow and ice from roadways, railways, and transportation structures. Earlier thaws and less snowpack and snow cover may increase the accessibility of seasonal mountain passes, although this could increase demands and season-lengths for maintenance and repair (CDOT 2013).

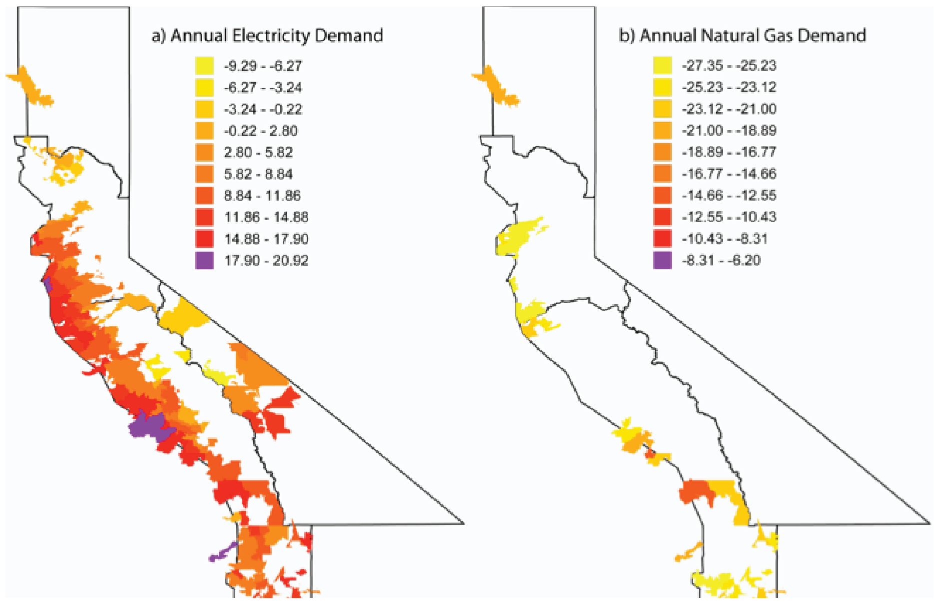
Heavier rainfall events are likely to cause periodic flooding of roadways and railways, and in some cases, erosion or mudslides. In addition to flooding and damages transportation corridors, transmission lines, wastewater treatment facilities, culverts, canals, tunnels, runways, and railways are likely to be challenged, with associated service and business interruptions (CDOT 2013). As dry spells grow longer, frequencies and risks of forest fires, with attendant transportation disruptions and infrastructure damage, will increase in many parts of the Sierra Nevada region. Radke et al. (in review) analyzed highway, railway and pipeline infrastructures of the transportation-fuel sector in the Dutch Flat area near the I-80 corridor. They found that wildfire is the predominant risk under climate change, due to a combination of direct exposure of the structures to wildfire, impacts on supporting facilities and agents, and increased competition for help from the State's emergency management systems.

Hydroelectric generation may be impacted adversely by climate change, but electricity demands within the region may be more shielded (by overall cool climes) in the mountainous parts of the region.

Sierra Nevada hydroelectric systems account for well over half of the state's hydropower generation (Madani et al. 2014) and rely on melting snowpack for operations. A declining Sierra Nevada snowpack may reduce the amount of water available for hydropower generation during late spring and summer when energy demand is high (CNRA 2009) unless reservoir operations can be modified to accommodate changed snowmelt regimes and impacts on aquatic ecosystems (Nelson et al. 2016). Responses to the change in seasonality of water resources available for hydropower generation will be complicated by changes in hydroelectricity demand brought on by climatic changes (Madani et al. 2014). For example, warmer winter temperatures will require less heat while hotter summer temperatures will increase power demand. Increased frequencies and magnitudes of floods (Das et al. 2013) will likely require reservoir operators to release more water to less hydroelectricity-generation advantage while retaining less water for the dry months.

Warming in the Sierra Nevada region is projected to lead to modest changes in residential electricity demand (Fig. 3.4.1; Auffhammer, in review) across most of the range and region. Electrical demand generally only increases when temperatures rise above about 65ºF, which is when air-conditioning demands start to rise. Much of the Sierra Nevada region—with its cool temperatures—is largely shielded from these increases, even under future warming scenarios. However, residential electrical demands on the western foothills of the Sierra Nevada on the ramparts of the Central Valley are projected to increase by 5 to 25% of historical totals (Fig. 3.4.1a). Demands for natural gas are projected to change rather little or decline as residential-heating demands decline (Fig. 3.4.1b).

FIGURE 3.4.1



Potential increases in (a) annual electricity demand and (b) annual natural-gas demand, as percentages of historical, by the end of this century for RCP8.5 for the residential sector, from Auffhammer (in review).

Emergency management may be impacted directly by climate change or indirectly by degrading emergency-management capacities generally.

The Sierra Nevada region is vulnerable to many hazards, including earthquakes (with Nevada, Tuolumne and Kern counties ranking this hazard risk particularly high in local hazard mitigation plans; LHMP; CalOES 2018), volcanos (especially along the eastern Sierra Nevada), floods (with Sierra, Nevada Placer, Amador, Calaveras, Mariposa, and Kern LHMPs ranking this particularly high hazard), fires (Modoc, Sierra, Nevada, Placer, Calaveras, Tuolumne, Mariposa, and Kern counties ranking this high hazard), avalanches (particularly risky in the steep terrains of the Sierra Nevada), landslides, dam and levee failures, severe weather (including dust storms), hazardous-material spills (risks concentrated mostly along the highway and rail corridors along Interstate 80, Highway 70, and Tehachapi Pass), disease, and disruptions of utility, food and water supplies (Safeguarding California 2016b). Not only will climate change cause or exacerbate some of these hazards directly but—without proper planning and implementations—it may degrade some capabilities to respond and recover from even those hazards that are not climate mediated.

The adequacy of current emergency response capacities in the face of such hazards is continually assessed by the State, working with local governments, the private sector, tribal governments, and federal agencies. Since 2015 (California SB379), LHMPs have been required to consider climate change during development and updates, but methods and strategies for doing so are just getting started (Stults 2017). To date, hazard mitigation plans (nationwide) have typically placed a stronger emphasis on emergency-response capacities than proactive hazard mitigation, and on structural designs and responses ("hard solutions") rather than strategies that use nonstructural, land-use or natural-system defenses (Stults 2017). In fact, likely changes in risks and severities of various hazards under climate change will need to be integrated into all four phases of emergency management if the region's emergency services and plans are to keep pace with the challenges of coming decades. The California Office of Emergency Services is developing and providing guidance and tools, in partnership with the full range of Federal, State, and local agencies and institutions, to support improved integration of climate-change information and concerns into emergency services and hazards mitigation planning (http://www.caloes.ca.gov/cal-oes-divisions/hazard-mitigation/hazard-mitigation-planning/state-hazard-mitigation-plan).

4: Regional Knowledge & Resource Gaps

Our current state of knowledge regarding climate change in the Sierra Nevada is robust, based as it is on several decades of research and observations. Each year, new "natural experiments" (like the great drought of 2012-2016 and the epic storms of 2017) and continuing research and observations teach us more and alert us to new aspects and challenges that climate change will bring. Nonetheless, gaps in data, monitoring, research, and policy remain. Some of the gaps identified earlier in this report, or in discussions with scientists and stakeholders who are active in the region, include:

Climate

- Climate monitoring is fundamental to our ability to extrapolate weather, climate changes, water resources, and ecosystem status from the limited number of stations and plots that function in remote areas of the region to whole basins and management units. Recent efforts by the NASA Airborne Snow Observatory (Painter et al. 2016) are filling in such gaps but more site-specific stations and data are needed for monitoring of many other weather and water conditions. The difficulties in maintaining and operating various monitoring equipment and methods in the many steep, remote, and isolated parts of the region have resulted in a paucity of monitoring stations and histories compared to most other parts of the state. More monitoring, especially in remote and unsullied parts of the region, is needed and should be welcomed.
- Temperatures, precipitation, snowpack, and streamflow have been monitored at many weather and snow stations in the region for decades. Other climatic measurements (sunshine, humidity, winds, air quality, and so on) are much less commonly made and maintained, and are needed if we are to detect, track, forecast, and manage for all aspects of the coming climate changes.

Wildfire

- Better understanding, models, and predictions of the processes and management of vegetation transitions following extreme fires, extreme drought and pest-caused forest die-offs are needed. At the range scale, remote sensing and existing monitoring efforts are allowing us to track large scale die-offs, broad landscape changes, and changes and challenges to a few key species; however, more attention and investment in higher resolution monitoring needed to track and predict local and specific changes are needed.
- A fundamental change projected to continue in coming decades is the thinning and loss of the region's snowpacks. Improvements are needed in understanding of how snowpack declines, and associated exacerbation of droughts, across the region will impact wildfire risks and the capacity of the region's vegetation, especially large trees and old growths, to accommodate climate change and capture and store carbon.
- Wildfire is expected to increase in frequency and intensity in many parts of the region. Improved information regarding developing and future impacts of extreme fires on human communities and landscapes is needed. The relations between forest-mortality events, like that associated with the recent drought, and wildfire risks and impacts need to be better understood and predicted. More information regarding tradeoffs between the air-quality impacts of uncontrolled wildfires and prescribed fires on air quality is needed.

- In terms of specific forest-resilience policies, the February 2018 Little Hoover Commission report "Fire on the Mountain—Rethinking Forest Management in the Sierra Nevada" (Little Hoover Commission, 2018) and the April 2018 Legislative Analyst's Office report "Improving California's Forest and Watershed Management (Taylor, 2018) provide many recommendations highlighting the importance and difficulties of restoring forest health and resilience, and some sweeping administrative changes that may be required to make headway.

Water

- Water-supply declines from increased water demands and from hydrologic changes associated with climate change will impact the region's environment and economy. Because communities and water supplies in the region are small and often remote, data to quantify changing supplies and water qualities, and to provide projections for planning and mitigation efforts, tend to be limited. Although efforts to better quantify likely impacts of climatic extremes and changes on the region's water supplies, quality, and hazards are being made by a variety of agencies and organizations, even more improvements are needed.
- Additional surface-water monitoring is almost always useful in this heavily surface-water dependent but data-limited region. Nonetheless, although measurements of surface-water discharge, temperature, and quality are available at many sites and have longer historical records in the region, groundwater observations and monitoring are sorely lacking. Because of their small catchments, groundwater supplies in many of the higher elevation areas are likely to be even more vulnerable to climate change than many better-established surface-water supplies. Groundwater supplies in these small catchments can respond quickly (and, in some cases, nearly irreversibly) to local overdrafts and to changes in snowfields and local recharge rates and timing. Cataloging and monitoring high-elevation springs, intermittent headwater streams, meadow water tables, and upland water tables and water quality will provide early warning of changes to come farther downstream and will allow for better-informed management of the region's water resources. In many communities and counties, information regarding the current status and trends of groundwater are lacking almost entirely. Thus, generally speaking, better data are needed to characterize and manage current groundwater situations, particularly in the fractured rock aquifers of the northern Sierra Nevada and Modoc Plateau.
- Flood risks are projected to increase within and downstream from the Sierra Nevada as climate change increases storm intensities and temperatures. However, accurate estimates of the coming changes in flood characteristics (e.g., flood frequencies and magnitudes, flood durations, seasonal timing) have yet to emerge and are much needed by communities, engineers, and hazards-managers in the region. Improved projections of future flood frequencies and risks—along with closely related projections of water-supply benefits and environmental and community impacts—are necessary as a part of debates regarding new reservoir-storage options in the region.

Communities

- Community-level metrics are essential to clarify community socioeconomic conditions, capacities for responding to climate change, and future growth and development challenges. However, comprehensive community-level data are not readily available throughout the Sierra Nevada. Efforts are underway to re-assess community capacity as part of the State's IRWM Program, with special focus on disadvantaged communities. More data and more attention to community adaptive capacities will generally allow for more informed policies and responses to climate change.

- Agency-community collaboratives focused on restoration of various aspects of landscape and community resilience offer important avenues for rebuilding capacities of communities to respond to climate change. However, entrenched agency cultures can be resistant to these new strategies and, along with low levels of existing community capacity, are challenges that will need to be surmounted to take advantage of these options.
- Combinations of community-responsive forest-management contracts and investments in community-scale wood utilization offer new pathways to forest restoration. However, these efforts are just beginning and methods for accurately monitoring and assessing benefits are needed. Greater experience and attention to these options are needed to ensure that resources flow to the most effective restoration options and that communities benefit from these activities.
- Adaptation efforts are not necessarily complete when a law has been passed or a regulation or plan has been adopted and enacted. Businesses and agencies that are unhappy with a policy or action can turn to the courts. As a result, communities and decision makers have to consider the possibility of legal challenge in their decision-making (Coglianese and Starobin, 2017). The success of adaptations often will depend on policies and actions beyond their immediate boundaries (Segall and Hults 2017), and local efforts may eventually find themselves at odds with each other, and in court. Local to regional adaptation efforts will benefit greatly if the uncertain legal environment can be stabilized and clarified, and if actions can be integrated across jurisdictions to reduce conflicts and legal risks.
- The levels of confidence and climate-model consensus sketched in Section 2 can serve as a practical guide for future vulnerability assessments and adaptation planning. First, the projections have highest unanimity and confidence regarding future warming and its consequences. Similarly, the projections have high confidence in enhanced storms, floods, warm-season drying, and long-term droughts. Assessments and planning will do well to focus initially on these projections as primary anchors for analysis. On the other hand, no clear consensus exists regarding whether overall precipitation will increase or decrease in coming decades, and projected long-term changes tend to be significantly smaller than year-to-year precipitation fluctuations throughout the 21st century. Consequently, in this regard, present-day assessments and adaptation planning would do well to focus on increasing robustness to a broad future range of precipitation trends rather than focusing on specific projections or even directions of change.

Hazards, Health and Emergency Management

- The last comprehensive community-health study of the Sierra Nevada Region was completed by the Sierra Nevada Ecosystem Project in the mid-1990s. Other than isolated studies of communities and counties, the latter of which involves units too general to adequately capture local socioeconomic conditions and outcomes, there are even fewer studies that connect landscape or ecosystem management outcomes and community health and wellbeing. The more recent socioeconomic analyses completed for three Collaborative Forest landscape Restoration projects in the region attempt to do this, but they are geographically limited and only loosely make causal linkages between landscape management and community outcomes. Thus, piecing together isolated and narrowly targeted public-health studies with generally anticipated climate change impacts is a major challenge and inexact science at best.

- Although legal mandates now exist requiring that climate change be included in hazard- and disaster-planning efforts, exactly how to accomplish this within resource limits and given the many uncertainties about future weather and climate extremes remains unclear. Enhanced extreme and hazardous events are likely to be a primary way that climate change threatens communities and landscapes in the Sierra Nevada region in the next few decades. Thus progress, decision-support tools, and good examples of how to best anticipate, prepare for, and recover from climate-change-modified hazards are much needed.

More gaps exist, of course. These, though, have risen to the top in our discussions with various stakeholders and peers from the region.

5: Conclusions

The Sierra Nevada is the resource backbone of California that provides vital supplies of fresh water, clean power, working lands, and wild places. Climate change in response to increasing greenhouse-gas concentrations in the atmosphere is projected to warm the region by 6 to 9° F by the end of the 21st century. At the same time, precipitation variability on all time scales is predicted to increase. As a consequence of this warming, snowpacks are expected to decline significantly, especially in the northern Sierra Nevada, with resulting changes in seasonal streamflow and increases in summertime dryness. The combination of warmer temperatures and greater precipitation variability are expected to increase flood risks while also increasing the prevalence of droughts. These changes in climate pose daunting challenges to the region's landscapes, resources and communities, including:

- **The fire regime.** Fire is a major driver of the ecosystems of the Sierra Nevada region. The warming and drying trends are projected to increase the frequency and severity of wildfire. A progressively altered fire regime is a primary and acute risk to the flora, fauna, and people of the Sierra Nevada region. High-severity wildfires have the potential to transform landscapes, perhaps irreversibly, thereby threatening communities, critical infrastructure, and transportation. The smoke produced by wildfire is a serious threat to human health.
- **Ecosystems and biodiversity.** The temperature increases and greater precipitation variations (especially increased droughts) are likely to stress and, in many cases, perturb terrestrial and aquatic communities. Species-range shifts in response to warming along with life history adaptions to the altered climate will produce novel ecological communities. The form and function of these new communities are unknown but they have the potential to generate sweeping changes in species composition and ecosystem services.
- **Water resources.** The increases in winter storms along with longer summer droughts are expected to challenge the region's water supplies and water quality, and thus—because of the primary role of Sierra Nevada streams in California's state-scale water management--will also challenge water systems across much of the state. Most of the water systems serving communities within the region are small and rely on local supply sources. These limited portfolios make many of the region's water supplies vulnerable to the large hydrologic changes to come. Even the region's groundwater is vulnerable through changes in groundwater pumping as local surface supplies deteriorate, as recharge patterns and rates change, and due to the generally smaller scale of so many of the region's aquifers (especially in granite-dominated terrains of the southern and central Sierra Nevada).
- **Communities.** Sierra Nevada communities are inextricably linked to the natural systems that surround them. Thus the environmental disturbances caused by climate change directly impact the well-being of these communities. For example, forest-dependent communities are at particular risk from severe wildfires and forest change; agricultural communities from impacts by changes in weather extremes and possible water-resources declines; and tourism-dependent communities from snowpack, aquatic, and landscape degradation.

Agencies, communities, and other organizations throughout the region are already at work on a wide variety of adaptive measures that are improving the condition of present-day landscapes and communities as well as providing improved prospects in the face of coming climate changes. Current examples of efforts to adapt include:

Ecosystems and Biodiversity:

- The Sierra Nevada Watershed Improvement Program led by the Sierra Nevada Conservancy and U.S. Forest Service, aims to restore the health of primary Sierra Nevada watersheds through increased investment and needed policy changes.
- A growing number of teams working to improve forest health and to reestablish wildfire to its proper place in the region's ecosystems, including the Fire MOU Partnership, several major activities in the Lake Tahoe Basin, several Collaborative Forest Landscape Restoration Projects, and local programs like the French Meadows Forest Resilience Project.
- Meadow-restoration efforts, including those of the Sierra Meadows Partnership and the Native Youth Conservation Corps.

Water Resources:

- Fifteen Integrated Regional Water Management regions, and planning efforts spawned by the Sustainable Groundwater Management Act.
- More local initiatives like the Lake Almanor Watershed Group and South Lassen Watersheds Group that are addressing water quality and quantity, and forest health issues, in their areas.

Community Adaptation Capacity:

- Tribal efforts to enhance water, wildfire, and food security, and to prepare for climate change on their lands and surroundings.
- Community collaborative efforts by coalitions like Amador-Calaveras Consensus Group and California Healthy Impact Product Solutions groups.
- Climate-smart land-preservation activities like those by Point Blue Conservation Science and the California Council of Land Trusts.
- Climate-smart development activities like those by the Sierra Nevada Alliance and Sierra Green Building Association.

Some of the most productive ways forward involve collaborative, regionally integrated, and multi-objective efforts across and between communities and agencies. Collaborations that promote stakeholder engagement and active partnerships not only encourage local solutions but also help to engage resources and capabilities harbored in institutions and communities across the region and state.

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